UNIVERSITI TEKNOLOGI PETRONAS

Approval by Supervisor

The undersigned certify that they have read, and recommend to The Postgraduate Studies Programme for acceptance, a thesis entitled

Electroosmotic and Electrochemical Methods in Stabilizing Kaolinite Soil in Ground and Slope Conditions

Submitted by

Syed Baharom Azahar bin Syed Osman

For the fulfillment of the requirements for the degree of

Degree of Doctor of Philosophy in Civil Engineering

Date: 1st June, 2008

Signature : _____

Main Supervisor : Assoc. Prof. Dr. Madzlan bin Napiah

Date : 1st June 2008

Co-Supervisor : Assoc. Prof. Ir. Dr. Ibrahim bin Kamaruddin

Assoc Prof Dr Madzlan Napiah
Associate Professor
Civil Engineering Department
Universiti Teknologi PETRONAS
Bandar Seri Iskandar, 31750 Tronoh,
Perak Darul Ridzuan, MALAYSIA.

UNIVERSITI TEKNOLOGI PETRONAS

ELECTROOSMOTIC AND ELECTROCHEMICAL METHODS IN STABILIZING KAOLINITE SOIL IN GROUND AND SLOPE CONDITIONS

By

SYED BAHAROM AZAHAR BIN SYED OSMAN

A THESIS

SUBMITTED TO THE POSTGRADUATE STUDIES PROGRAMME

AS A REQUIREMENT FOR THE

DEGREE OF DOCTOR OF PHILOSOPHY

CIVIL ENGINEERING

BANDAR SRI ISKANDAR

PERAK

JULY, 2007

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

Signature: 

Name : Syed Baharom Azahar bin Syed Osman

Date : 1st June 2008

ABSTRACT

Electrokinetic method of stabilization offers an innovative alternative to the improvement of soft soil and problematic ground condition. This research investigates the effects of electroosmotic and electrochemical on local kaolinite soil in both flat ground and slope conditions. This paper also concentrates on finding out the best possible combinations of controllable variables which provide optimum modification and stabilization effects using both the methods.

The first stage involved the usage of direct electrical current and electrodes in electroosmotic application associated with soil consolidation and stabilization. A small scale electroosmotic tests on kaolinite soil were conducted using specially designed and fabricated electroosmotic cells and boxes. The effects of variation in surcharges, voltages, electrodes, different sizes of particles and others on the characteristics of soil such as settlement, shear strength, moisture content were then compared. In the second stage experiment, several tests were conducted in electrochemical cells and boxes using different voltages, chemicals, molarities, spacings of electrodes, and other variables introduced in the soil sample. The outcomes of all these varying variables on the treated soil samples were then monitored and recorded.

Results from both the electroosmotic and electrochemical treatments demonstrate positive effects on the treated kaolinite soil samples. The electroosmotic treatment using 100 volts produced an increase in shear strength of approximately 450 percent after 7 days of treatment mainly due to dewatering and flocculation processes. The electrochemical method using 100 volts on the other hand resulted in a stunningly 2200 percent increase in shear strength using calcium chloride ($CaCl_2$) solution with the same 7 day period of treatment possibly as a result of the formation of cementitious material. Likewise, other soil characteristics also show significant improvements after treatment.

ABSTRAK

Kaedah rawatan elektrokinetik menawarkan satu kaedah altenatif untuk merawat tanah yang lembut dan tanah yang bermasaalah. Kajian ini menyelidiki kesan daripada kaedah elektroosmotik dan elektrokimia ke atas tanah kaolinit dalam kedua-dua keadaan rata dan cerun. Kertas kajian ini juga menumpukan perhatian kepada mencari kombinasi pembolehubah terkawal yang akan memberi kesan modifikasi dan kestabilan yang maksima dalam menggunakan kedua-dua bentuk rawatan di atas.

Peringkat pertama kajian melibatkan penggunaan arus terus elektrikal dan elektrod dalam applikasi yang berkaitan dengan proses pengukuhan dan penstabilan. Ujian-ujian elektroosmotik berskala kecil ke atas kaolinit dijalankan dengan menggunakan sel-sel dan kotak elektroosmotik yang direkabentuk khas. Kesan dari variasi bebanan, voltan, elektrod, saiz tanah yang berlainan dan yang lain-lain ke atas ciri-ciri tanah saperti pengenapan, kekuatan riceh dan kandungan lembapan kemudiannya akan dibandingkan. Di dalam ujian peringkat kedua, beberapa ujian di jalankan dalam sel-sel dan kotak elektrokimia dengan mempelbagaikan voltan, jenis kimia, molar, jarak elektrod dan lain-lain pembolehubah. Natijah daripada pembolehubah yang berlainan ke atas tanah yang dirawat kemudiannya akan diawasi dan direkodkan.

Keputusan daripada kedua-dua kaedah rawatan elektroosmotik dan elektrokimia mempamerkan kesan yang positif ke atas tanah kaolinit yang dirawati. Rawatan elektroosmotik menggunakan voltan 100 V telah menghasilkan pertambahan dalam kekuatan riceh sebanyak lebih kurang 450 peratus selepas jangkamasa rawatan 7 hari yang mana pertambahan kekuatan riceh ini adalah disebabkan olih proses pengurangan air dan flokkulasi. Kaedah elektrokimia menggunakan voltan 100 V dan kalsium klorida sebagai anolit pula telah menghasilkan pertambahan kekuatan riceh sebanyak 2200 peratus selepas jangkamasa rawatan yang sama selama 7 hari. Penambahan kekuatan riceh ini adalah berkemungkinan disebabkan olih pembentukan bahan bersimen yang lebih kukuh. Saperti mana dengan kekuatan riceh, lain-lain ciri tanah juga menunjukkan keadaan yang lebih baik selepas rawatan.

ACKNOWLEDGEMENT

First and foremost, my utmost gratitude goes to Allah All-Mighty, Most Gracious and Most Merciful for bestowing the much needed strength, courage, and knowledge in completing this research.

Of course, my deepest gratitude also goes to my main supervisor, Assoc. Professor Dr. Madzlan bin Napiah whom through him, Allah All-Mighty has made it possible for this research to materialize. I sincerely believe, it would have been difficult and somewhat without direction if not for his support, guidance, and advices throughout the duration of this work.

I would also like to extend my thanks to my co-supervisor, Assoc. Professor Dr. Ir. Ibrahim bin Kamaruddin for all his support and assistance.

My thanks to all of my collegues in the Civil Engineering Department for providing many helpful advices and suggestions. In many occasions, the technologists especially Zaini, Idris, Johan and the rest have kindly and willingly assisted me. I am also extremely indebted to my wife, children, and family members for their prayers, encouragements, and of course patience from day one.

Finally, my heartfelt thanks to all the staffs in the department of post graduate studies, department of human resources, department of finance, and University Technology Petronas as a whole.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

A cross-sectional area (L^2)

c_i concentration of chemical species (ML^{-3})

c_v coefficient of consolidation (L^2T^{-1})

D dielectric constant

D_i^* effective diffusion coefficient (L^2T^{-1}) of species i

F Faraday's constant

h hydraulic head (L)

I electric current density (AL^{-2})

i_e voltage gradient

J current density

J_i diffusion mass flux of species i per unit area ($MT^{-1}L^{-2}$)

k_e coefficient of electroosmotic permeability ($L^2V^{-1}T^{-1}$)

k_i electroosmotic water transport efficiency

k_h hydraulic conductivity (LT^{-1})

L length between electrodes

ΔL length of soil sample

m positive integer

m_v coefficient of volume compressibility

n porosity

q fluid flux per unit area due to hydraulic gradient ($L^3T^{-1}L^{-2}$)

q_e electroosmotic flow rate

T_v time factor

u_e pore water pressure

$\overline{U}$ average degree of consolidation

v_e flow velocity due to electroosmosis

V_m maximum voltage

V_x voltage at any particular point

ΔV potential difference

W amount of water transferred per unit charge

x distance from cathode

x longitudinal distance (L)

z_i charge of ion i

ζ potential across the capillary (zeta potential, V)

η viscosity of pore fluid (FT/L^2)

σ specific conductivity of the soil

σ^* effective electrical conductivity (SL^{-1})

γ_w unit weight of water

$\rho(x)$ resistivity of soil at position x

ϕ electric potential (V)

u_i^* effective ionic mobility of ion ($L^2V^{-1}T^{-1}$)

Chapter 1
INTRODUCTION

1.1 General

Soft and problematic soils are found in abundance throughout the world and are characterized by low shear strength and high compressibility that result in extensive settlement and foundations failure under structural loading. The construction and installation cost of the structures are enormous, and the consequence of failure can be catastrophic. Over the last few decades, geotechnical engineers have been increasingly challenged to improve soil condition using better techniques which are economical, less time and labour consuming, and more effective in treating problematic soil. One of these techniques, first incepted by Reuss in 1809 (cited from Kassim et al., 2003) known as electrokinetic stabilization, has been used increasingly eversince its first practical application by Cassagrande in 1951.

Today, electrokinetic technique in geotechnical engineering is a part of the many techniques found in soil stabilization and improvement. Electrokinetic have been applied as a soil improvement method in projects such as the stabilization of earth dams, railways embankments, and slopes. Besides stabilizing soil, electrokinetics have also been used for treating and removing contaminants in soil especially in industrial contaminated land and landfill areas. However, electrokinetic strengthening and stabilization, even if recognized for many years as an interesting potential, remains today very seldom used in practice especially in Malaysia.

In Perak, kaolinite soil is found in abundance and scattered throughout the state especially in the Tapah-Bidor area. It is a well known fact that ground and especially slopes which consist of kaolinite soil are highly prone to failure due to its inherent characteristics such as being weaker in shear strength when compared to the laterite clay type of slope. In many cases, whenever kaolinite soil is located close or adjacent to laterite clay on slopes, it could be seen that the kaolinite section will have an earlier failure. Concerns have been voiced by the local authorities such as Jabatan Kerja Raya in Perak on the rate of failure of kaolinite slopes. In fact, a few contractors specializing in soil which the author has personally met have also expressed their frustrations in dealing

with kaolinite soil due to its tendency to fail repeatedly after completion of rehabilitation works. Hence, the need to embark into a research looking for a feasible alternative in addressing the problems associated with the local kaolinite soil is very necessary. Although elsewhere in different parts of the world many studies have been conducted on various types of soils using electrokinetic treatment, there has only been a handful of study done on electrokinetic treatment on our native Malaysian soils. Kassim et al. (2003) for example have conducted several tests on a type of local tropical residual soil using different combinations of anolytes and catolytes and observed positive results in those tests. Syed (2000) performed laboratory electroosmotic treatment on marine soil from Bidor and slime from ex-mining sites in Tronoh and results showed improvements in the properties of both materials. However, the current knowledge and understanding on the various kinds of local soils suitable for both electrokinetic/electrochemical treatments indicate that a more extensive study is necessary.

Therefore, the focus of this research is to look into the possibility of treating kaolinite soil type using electroosmotic and electrochemical method of treatment.

The objectives of the study are summarized as follows;

i. Investigating the phenomenon of electroosmotic and electrochemical effects on selected local kaolinite soil by subjecting them to different test conditions. This was achieved by varying the following variables;
   a. Surcharges
   b. Voltages
   c. Types of electrodes
   d. Spacings of electrodes
   e. Arrangements of electrodes
   f. Connections of electrodes
   g. Particles passing different sizes of sieves
   h. Types of chemicals
   i. Molarities of chemicals
ii. Establishing the best possible combinations of variables given above from (a)-(i) for treatment using both methods on both flat ground and slope conditions.

iii. After conducting the experiments under different conditions, a final conclusion could be drawn as to whether electroosmotic and electrochemical treatments on the selected kaolinite soil produce positive effects or vice versa.

The results and data established from the study hopefully will in future help to produce a reliable method in strengthening kaolinite soil on both ground and slope conditions. It is also hoped that the early findings of the best possible combinations within this limited research duration will eventually lead to the final establishment of optimum combinations of variables to be utilized later in actual treatment at site.

1.2 Layout of thesis

Five chapters are presented in this thesis.They are comprised of the following;

Chapter 1 – provides introduction and layout of the thesis.

Chapter 2 – literature review on two major topics; electroosmosis and electrochemical process covering basic theories, factors influencing both processes, and past/present findings and applications.

Chapter 3 – detail of equipments, set-up of experiments, and testing procedures. This chapter is consisted of three main sections covering the basic tests on soil properties, and the more advance electroosmotic and electrochemical series of tests.

Chapter 4 – mainly presents the results and analysis of all the electroosmotic and electrochemical tests conducted on the kaolinite soil.

Chapter 5 – presents the conclusion of the research and recommendations for future studies.

CHAPTER 2
LITERATURE REVIEW

2.1 Electroosmosis

In 1809, Reuss was probably the first man to observed when a direct current was applied to a clay-water mixture using two electrodes, the pore water in the soil flows from anode to cathode. When the electric potential was removed, the flow of water immediately stopped. This phenomenon is termed electroosmosis. Hence, electroosmosis is a process of transferring free water in the capillaries of the soil under the influence of electrical potential. In fact, when two electrodes are embedded in fine grained soil are connected to opposite polarities on a direct current supply results not only in electroosmotic process but theoretically generates three basic distinct electrokinetic processes as shown in Figure 2.1 and elaborated as follows;

1. electrophoresis - the migration of charged colloids, not small ions, in solid-liquid mixture under electric potential gradient, where discrete particles are transported through water. If a direct current (DC) is applied to clay-water systems, negatively charged clay particles will migrate toward the anode. In a compact system of porous plug, electrophoresis is of less importance due to restrained solid phase.

2. electromigration - the movement of charged ions towards the oppositely charged electrodes relative to solution. In a dilute system or a porous medium with moderately concentrated aqueous solution of electrolytes, electromigration of ions is the major cause of current conduction. With regard to contaminated soils, electromigration is the primary mechanism of electroremediation when the contaminants are ionic or surface charged.

3. electroosmosis - involves water transport through a continuous soil particle network, where the movement is primarily generated in the diffuse double layer or soil

moisture film. The principle mechanism in electroosmosis is the migrating ions, where the cations migrate to the cathode and the anions move toward the anode. Accordingly, when an electric field (DC) is applied to a clay-water system, the surface or particle is fixed, whereas the mobile diffuse layer moves carrying solution with it.

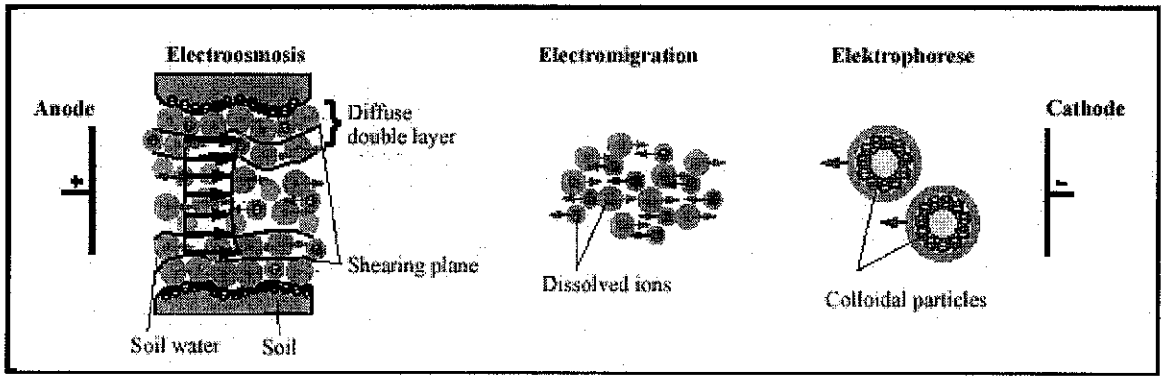


Figure 2.1 Electrokinetic transport process in a DC current field (after Wieczoreks et al., 2004)

The basis of electroosmotic theory is that cations are attracted to a cathode and anions to an anode. These ions (cations and anions) exert a viscous force on the water surrounding them as they migrate towards their respective electrodes. Due to the nature of clay formation, which usually results in significantly negative charged clay particles, the predominant ions within the pore fluid are therefore cationic. In other words, a soil containing negatively charged clay particles has a number of cations far exceeding the number of anions. Thus, the net water flow is in the direction of the cathode (Mitchell, 1991).

The above explaination is actually based on the Helmholtz –Smoluchowski's theory, which is the most widely accepted theory for electroosmosis apart from other theories such as Schmidt and Spiegler theories. In a more elaborate explanation, Helmholtz-Smoluchowski theory is based on the concept of a diffuse double layer system surrounding the clay particles as shown in Figure 2.2. The inner wall of the double layer which is relatively thin compared to the outer wall, consists of negatively charge ions

strongly attached to the wall. The outer wall consists of moveable positive ions. Immediately adjacent to the double layer is a portion of free water.

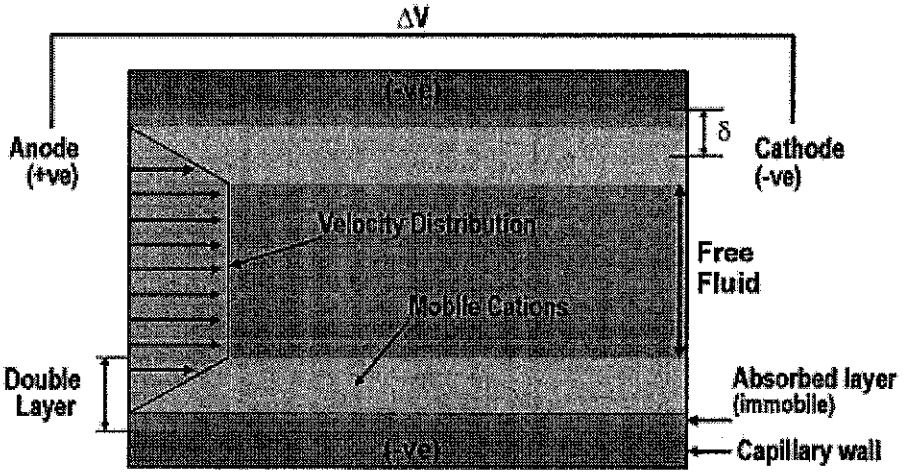


Figure 2.2 Helmholtz-Smoluchowski model for electroosmosis flow (after Mitchell, 1993)

When a direct current is applied, the mobile positive ions will be attracted towards the cathode, dragging with them the free water molecules causing a general movement of water from the anode to the cathode. The development of normal electroosmotic flow is shown in Figure 2.3. The Helmholtz-Smoluchowski's theory indicates that the flow rate through soil capillaries is governed by the electrical force causing flow and the frictional force opposing flow (Mitchell, 1993) and is given by the equation;

$$q_e = k_e i_e A \tag{2.1}$$

where q_e = electroosmotic flow rate

k_e = electroosmotic permeability

i_e = voltage gradient

A = cross-sectional area

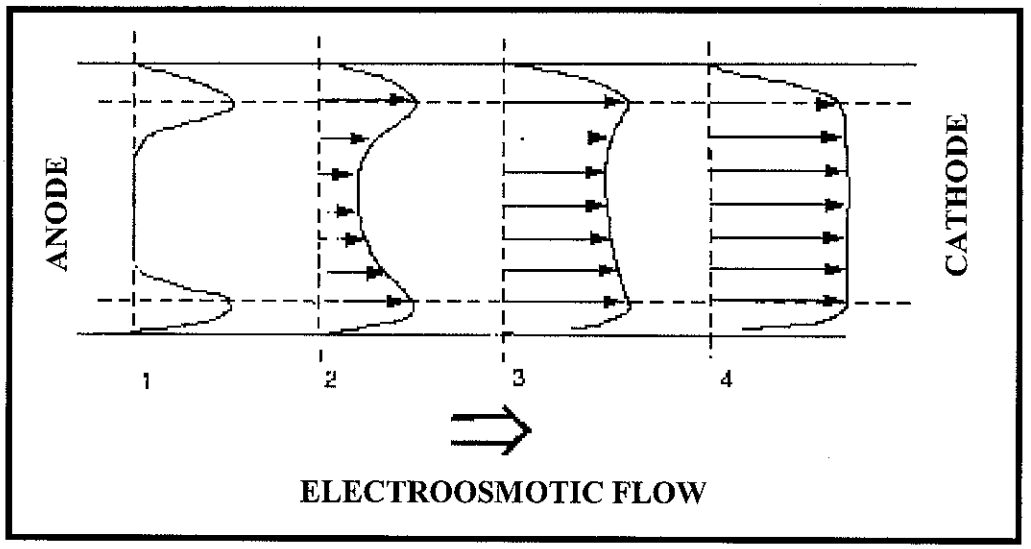


Figure 2.3 Development of electroosmosis flow. Dashed boundary represents the shear plane where zeta potential is measure (after Pamukcu, 1997)

Helmholtz first treated electroosmotic phenomena analytically in 1879. A mathematical basis was provided then. Pellet (1904) and Smoluchowski (1921) (cited from Pamukcu, 1997) later modified it to apply to electrophoretic velocity. From here, the overall mathematical treatment of the Helmholtz- Smoluchowski's model for electroosmotic flow resulting from an applied electric field is given by the expression;

$$v_e = \left(\frac{\zeta D}{\eta} n\right)\left(\frac{\Delta V}{\Delta L}\right) \mathrm{A} \qquad (2.2)$$

where v_e = flow velocity due to electroosmosis

ζ = potential across the capillary (zeta potential)

D = dielectric constant

n = porosity

η = viscosity of pore fluid

ΔV = potential difference

ΔL = length of soil sample

A = cross-sectional area

In a cross sectional area, A having N number of capillaries, each having an area, a, the flow will be

$$q_e = \left(\frac{\zeta D}{\eta} n\right)\left(\frac{\Delta V}{\Delta L}\right) Na$$

Since Na is equal to A, equation 2.2 becomes

$$q_e = \left(\frac{\zeta D}{\eta} n\right)\left(\frac{\Delta V}{\Delta L}\right) A = k_e i_e A \qquad (2.3)$$

where q_e = flow rate due to electroosmosis

Equation 2.1 conforms to Darcy's law of hydraulic flow. The overriding benefit of electroosmosis, contrary to the case of hydraulic permeability, k_h, the electro-osmotic permeability k_e is shown to be independent to the pore size or the presence of macro-pores (Acar and Alshawabkeh, 1993). This is in contrast to the hydraulic permeability k_h, which decreases markedly with pore size as shown in Figure 2.4.

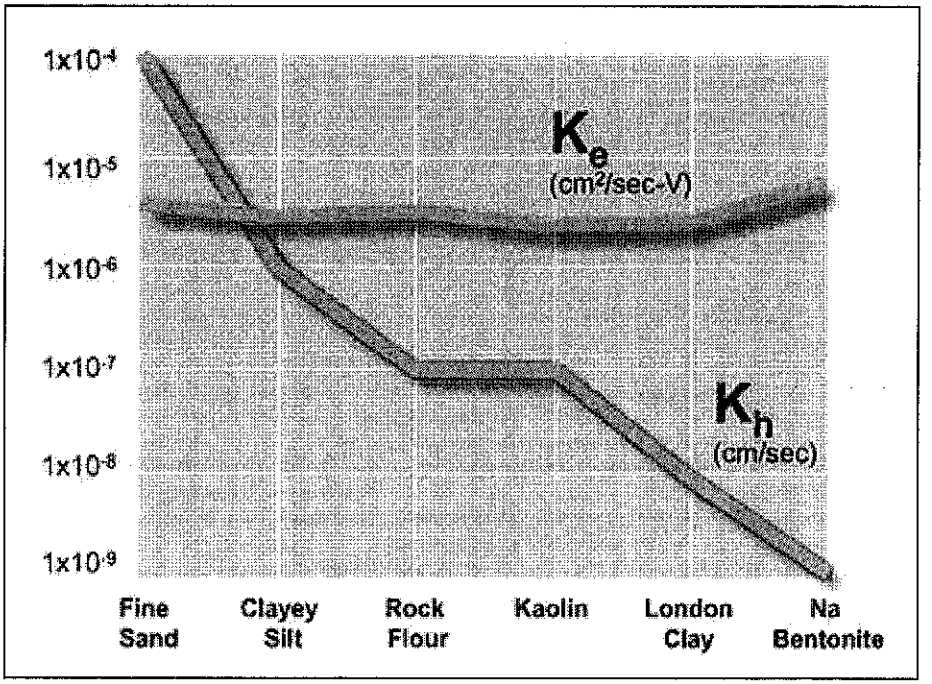


Figure 2.4 Electroosmosis performance over a range of soils (after Nuground, 2004)

In electroosmotic flow, virtually all the pore water moves except for the very thin rigidly attached part of the double layer. All the water flows at a constant velocity irrespective of the pore size. In the case of hydraulic flow, all the double layer remains stationary. It is also worth to note that equation 2.2 incorporates the value of zeta potential (ζ) which is a very important factor in the electroosmotic process. During electroosmotic stabilization, the soil's zeta potential will affect the movement of water molecules in the double layer. The zeta potential is defined as the potential between the stationary and moveable parts of the double layer surrounding the soil particles. The zeta potential is typically negative for clays and silts that are saturated and ranges from -10mV to -100mV (Probstein and Hicks, 1993). When zeta potential is negative, the electroosmotic flow will move towards the cathode. Yeung et al., (1997) noted that in most clays, the value of zeta potential is between 0 and -50 mV depending on the chemistry of the soil system.

Electroosmosis provides two major benefits when properly applied. First, electroosmosis provides uniform pore water movement in most types of soil regardless to the size of the pore. The movement of water from anode to cathode results in the consolidation between electrodes particularly in the vicinity of the anode proportional to the quantity of water removed. Transporting water away from the anode results in the development of negative pore water pressure, which in turn results in an increase in effective stress and a corresponding increase in shear strength. The entire soil mass between the electrodes is basically treated equally. In general the electroosmotic permeability for any soil at 20°C is around 1 x 10^{-5} cm/sec at 1 volt/cm. Many researchers and investigators have published different values of electroosmotic permeability, k_e. These are summarized in Table 2.1. The second major benefit is the electricity applied to the soil directly results in the heating of the soil. The soil warming not only increases the mobilization of volatile organics but also increases the electroosmotic permeability by lowering the viscosity of the pore water. The applied D.C. voltage and induced current provide resistive heating power to the entire soil mass between the electrodes. The current is a function of the soil electrical conductivity according to Ohm's law. Soils that are more electrically conductive will draw more current at a given voltage and generate more heat.

Table 2.1 Coefficients of electroosmotic permeability (after Mitchell, 1991)

Material	Water content *(%)*	k_e in 10^{-5} *(cm^2/sec-V)*	Approximate k_h *(cm/sec)*
London clay	52.3	5.8	10^{-8}
Boston blue clay	50.8	5.1	10^{-8}
Kaolin	67.7	5.7	10^{-7}
Clayey silt	31.7	5.0	10^{-6}
Rock flour	27.2	4.5	10^{-7}
Na-Montmorillonite	170	2.0	10^{-9}
Na-Montmorillonite	2000	12.0	10^{-8}
Mica Powder	49.7	6.9	10^{-5}
Fine sand	26.0	4.1	10^{-4}
Quartz powder	23.5	4.3	10^{-4}
As quick clay	31.0	20.0-25.0	2.0×10^{-8}
Bootlegger Cove clay	30.0	2.4-5.0	2.0×10^{-8}
Silty clay, West Branch Dam, USA	32.0	3.0-6.0	1.2×10^{-8} -6.5 x 10^{-8}
Clayed silt, Little Pic River, Ontario, Canada	26.0	1.5	2.0×10^{-5}

Electroosmotic method has been proven to be effective in stabilizing and consolidating soils both in the laboratory and in the field (Chappel and Burton, 1975; Mitchell and Wan, 1977). The electroosmotic consolidation induced the reduction of moisture content and increase in shear strength (Bjerrum et al., 1967; Lo et al., 1991; Shang and Dunlap, 1996). It was indicated from Casagrande's work that small reduction in moisture content by electroosmosis could produce significant increase in soil strength.

Electroosmotic treatment however, in some cases is not always effective. The relative contribution of electroosmosis, and ion migration to the total transportation of water varies according to the soil type, water content, types of ion species, pore fluid concentrations of ions and processing conditions. Electroosmosis treatment is only applicable in fine grained soils which include silts, clayey silts and fine clayey-silty sands and will be of no advantage to a coarser grain material such as sand with a hydraulic conductivity of $k_h \geq 50 \times 10^{-4} cms^{-1}$ (Casagrande, 1952).

2.1.1 Factors influencing the electroosmotic process

In general there are many governing factors which influence the electroosmotic process. When an electrical current is applied on a suitable soil mass, this will trigger electroosmotic process. In addition to water transport between the electrodes, oxidation and reduction take place as the electrons are transferred in and out of the system (Gray and Mitchell, 1967; Thomas and Lentz, 1990; and Mitchell, 1993). These two factors trigger the formation of other sequential effects influencing the effectiveness of the on-going electroosmotic process. The resulting effects are ion diffusion, ion exchange, mineral decomposition, precipitation of salts or secondary mineral, electrolysis, hydrolysis, oxidation, reduction, physical and chemical adsorbtion, and fabric changes (Mitchell, 1993). Some of the changes may be beneficial while the others may retard the efficiency of electroosmosis.

Hence, for the purpose of discussion, three major factors that influence the effectiveness of the electroosmotic process especially controlling the degree of water migration are given as follows;

i. Effects of soil chemistry

The rate at which pore water is moved through a soil-water system is dependant on;

a. the magnitude of the applied electric current
b. the chemistry of the soil-water system
c. the size and shape of the pores
d. the relationship between the inter-granular stress and the pore water tension
e. the availability of free water at the anode

Spiegler friction model (1958) showed that the electroosmotic water transport per unit electrical charge increase with increasing cation/water ratio in the system. Experimental evidence of this theory has been given by a number of researchers. The cation/water ratio factor is very important due to the fact that the economy and efficiency of electroosmosis are governed by the amount of water transferred per unit charged and electrosmotic water flow per unit charge, W, is proportional to the water:cation ratio in the diffuse water layer (Gray and Mitchell,1967). That is

$$W\,\alpha\,\frac{molar\,concentration\,of\,water}{molar\,concentration\,of\,cations\,within\,diffuse\,water\,layer}$$

Thus, in high cation exchange capacity clays with low water contents, W will be low as the water transferred per ion equivalent or quantity of electric charge will be low. From such relationship, it is possible to predict the behavior of clay in relation to its electroosmotic efficiency in condition where the clay has different values of water content, cation exchange capacity and cation:anion ratios between the diffuse water layer and free water system.

The amount of water transferred per unit charge is then quantified by the electroosmotic water transport efficiency, k_i, and it is related to the electroosmotic permeability by the equation

$$k_i = \frac{k_e}{\sigma} \tag{2.4}$$

Where k_e = electroosmotic permeability

k_i = electroosmotic water transport efficiency

σ = specific conductivity of the soil

As, k_e, varies within a relatively narrow limit, equation (2.4) shows that the electrosmotic efficiency measured by, k_i, is a sensitive function of the electrical conductivity of soil (Mitchell, 1993). The treatment is ineffective in soil with a high specific conductivity as the required current to establish a voltage gradient for the treatment will be too high. Field applications on soil with specific conductivities in the range of 0.02-0.03 siemens have proved that successful. However, treatment on soil with specific conductivity of 0.25 siemens is unlikely to be effective (Mitchell, 1993).

The specific conductivity of soil changes with water content, cation exchange capacity and the free electrolyte chemistry during electroosmosis (Acar and Hamed, 1990). A study by Gray and Mitchell (1967) indicates that electroosmotic efficiency decreases with a decrease in moisture content and increase in activity of the soil. Electroosmotic dewatering is independent to the variation in electrolyte concentration for active clays such as illite, while an increase in electrolytes tends to decrease the efficiency in inactive clays such as kaolinite.

ii. Electrolysis of the pore water

Application of direct current via electrodes immersed in water results in oxidation at the anode and reduction at the cathode by the following reactions (Acar and Alshawabkeh, 1993).

At the anode:

$$2H_2O - 4e \rightarrow O_2\uparrow + 4H^+ \qquad (2.5)$$

At the cathode:

$$2H_2O + 2e \rightarrow H_2\uparrow + 2OH^- \qquad (2.6)$$

Water molecules undergoing reduction at the cathode doubles the amount of water molecules undergoing oxidation at the anode. If the resulting ions are not removed or neutralized, an acid front (that is, an area of decreased pH) will develop at the anode, while a base front (that is, an area of increase pH) develops at the cathode. These fronts will migrate towards each other as hydrogen and hydroxide ions move under electrical gradient. When these two fronts meet, they form a neutralized zone of very low conductivity (Alshawabkeh and Acar, 1996). The voltage drop in this zone is very high and may render the process inefficient.

iii. Electrode reactions

The reactions that occur between the electrodes and the pore water depend on the characteristics of the pore water and the material properties of the electrodes. From corrosion theory it is known that oxidation of the hydroxide forming oxygen occurs at the anode owing to the loss of electrons while reduction of hydrogen from water occurs at the cathode (Owen and Knowles, 1994). Both the reaction at cathode and anode are as follows;

At cathode:

$$2H_2O \rightarrow H_3O^+ + OH^- \quad (2.7a)$$

$$H_3O^+ + e + M \rightarrow MH + H_2O \quad (2.7b)$$

$$MH + H_3O^+ + e \rightarrow H_2\uparrow + 2H_2O + M \quad (2.7c)$$

or

$$2H_3O^+ + 2e \rightarrow H_2\uparrow + 2H_2O \quad (2.7d)$$

or

$$4H_2O + 4e \rightarrow 2H_2\uparrow + 4OH^- \quad (2.7e)$$

As shown above, the principle reaction at cathode is the reduction of hydrogen from water (Potter, 1956), where M is the metal used as the electrode. This process results in an increase in the concentration of hydroxide ions, enhances the precipitation of metallic hydroxide and the liberation of hydrogen gas. The increase in hydroxide ion is indicated by an increase in the pH value in the vicinity of the cathode. Similar observations have been made by Eykholt and Daniel (1994) and Alshawabkeh and Acar (1996).

At anode, metal corrodes into its oxide and the oxidation of hydroxide ions form oxygen. The following equations described the chemical reaction;

$$2H_2O \rightarrow H_3O^+ + OH^- \quad (2.8a)$$

$$OH^- + M \rightarrow MHO + e \quad (2.8b)$$

$$MHO + OH^- \rightarrow MO + H_2O + e \quad (2.8c)$$

$$2MO \rightarrow O_2\uparrow + 2M \quad (2.8d)$$

or

$$4OH^- \rightarrow O_2\uparrow + 2H_2O + 4e \quad (2.8e)$$

or

$$2H_2O - 4e \rightarrow O_2\uparrow + 4H^+ \quad (2.8f)$$

The reactions at the anode result in the liberation of oxygen and the production of hydrogen ions. The increase in the hydrogen ions lowers the pH at the anode.

To simplify the equations above, for example if mild steel electrodes were used, the reaction will be as follows;

Oxidation at the anode

$$Fe \rightarrow Fe^{2+} + 2e^- \quad (2.9)$$

Reduction at the cathode

$$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^- \quad (2.10)$$

Thefore during the process of migration of ions

$$Fe^{2+} + 2(OH)^- \rightarrow Fe(OH)_2 \text{ Ferrous hydroxide} \quad (2.11)$$

Further oxidation

$$Fe^{2+} \rightarrow Fe^{3+} + e^- \quad (2.12)$$

As mentioned above, the chemical reaction described by equations (2.7a) to (2.8f) depends on the type of metal used as the electrodes. If copper is used as the anode, copper oxide is formed at the anode with little or no liberation of oxygen. If an inert material is used, such as platinum, oxygen will be liberated at the anode.

2.1.2 Theory of the development of pore water pressure

The theory of electroosmotic consolidation superimposes hydraulic and electric induced flows through an incompressible soil mass and assumes a one-dimensional flow condition where the electrodes are semi infinite plates. A comprehensive theory presented by Esrig (1968) explains the development of pore water pressures in soils due to the application of a uniform potential field. It is worth mentioning here that among the basic assumptions in developing the theory are;

i. The structure of the soil is uniform and the material is fully saturated.
ii. The physical-chemical properties of the soil mass are uniform throughout and constant with time.
iii. Electrophoresis of the fine-grained particles does not occur.
iv. There is a proportionality between the electrically induced velocity of water flow through the soil and the voltage gradient $\partial V/\partial x$.
v. All applied voltage is useful in producing water transport.
vi. The electric field throughout the soil mass is not altered with the passage of time.
vii. No reactions (such as electrolysis etc.) occur at the electrodes.
viii. Fluid flows due to an electric field, and due to a hydraulic gradient may be superimposed to find the total flow.

The theory above has been validated by Wan and Mitchell (1976) and they also confirmed that the nature of pore pressure developed would depend on the boundary conditions of the electrodes.

In electroosmosis, electrodes can be placed in an open or closed flow arrangement or better known as boundary conditions. Open flow arrangement constitutes the case when the ingress and egress of water are allowed at an electrode. In the closed flow arrangement, no ingress and egress of water are allowed. Different electrode configurations (open or closed) result in substantial variations in the pore water pressure developed across the soil specimen. Figure 2.5 presents a schematic diagram of the development of pore water pressure in a soil specimen under a constant current (or voltage) conditions.

In case **A**, the boundary condition is as such that both the anode and cathode are open whereby water is allowed to pass through behind the anode and would permeate through the soil to displace the pore fluid through the cathode. The resulting development of pore water pressure in the soil having this case **A** boundary condition is given by the following equation;

$$U_e = \frac{k_e}{k_h}\gamma_w\left(V_M\frac{x}{L} - V\right) \tag{2.13}$$

where U_e= pore water pressure

V_m = maximum voltage

V = voltage at any particular point

L = length between electrodes

x = distance from cathode

γ_w = unit weight of water

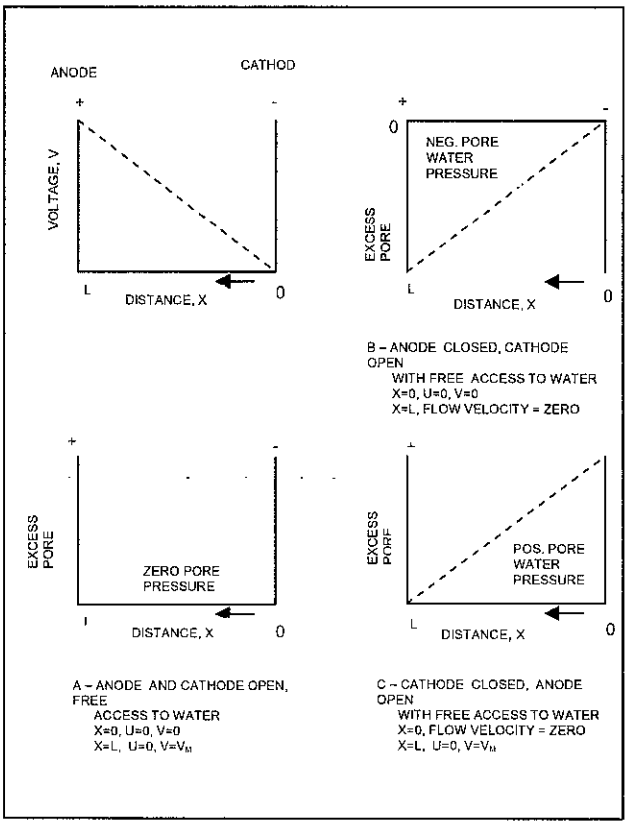


Figure 2.5 Pore pressure development in a uniform field (after Esrig, 1968)

Note that in a uniform field the term in bracket in equation (2.13) is always zero indicating that no pore water should develop in case A boundary condition. It should be noted however, during electroosmosis process, the possible change in ion concentration and pH might result in a production of non uniform electrical field. This non uniform electrical field generates negative pore pressure in the soil (Mise, 1964; Acar et al., 1994 and Alshawabkeh and Acar, 1996)

In case **B**, the anode is closed and the cathode is opened to permit the access of water. Since there is no water to replenish the soil at the anode end, negative pore pressure will develop. The magnitude of the negative pore pressure developed is given by the following equation in which the pressure developed at any particular point between the anode and cathode is proportional to its voltage.

$$U_e = - \frac{k_e \gamma_w}{k_h} V \qquad (2.14)$$

In case **C**, the cathode is closed and water is allowed to access through the anode (anode open). As water moves from anode to cathode during the electroosmosis process, positive pore water pressure are developed at the cathode. The magnitude of pore pressure generated is given by the following equation;

$$U_e = \frac{k_e}{k_h} \gamma_w \left(V_M - V \right) \qquad (2.15)$$

Esrig (1968) also developed related equations on the development of pore pressure with respect to the effect of electrode geometry. In the case where the electrodes are arranged so as to cause radial flow, he presented that for case B (open cathode, close anode) and case C (open anode, close cathode) for radial flow electrode geometry, the related equations are identical as given in equations (2.14) and (2.15). This indicates that the pore water pressure is only governed by the voltage at that point as previously discussed. The electrode geometry affects the pore pressure by determining the electric field and hence the voltage distribution (Hamir, 1997).

Other important aspects that affect the magnitude of pore water pressure are the applied current density and the resistivity of the soil itself. In fact equation 2.14 can be further developed by expressing it as functions of current density (J) and soil resistivity (ρ), (Lo et al., 1991).

$$U_e = \frac{k_e}{k_h} \gamma_w J \int_0^X \rho(x) dx \qquad (2.16)$$

where $\rho(x)$ = resistivity of soil at position x

J = current density

Equation 2.16 clearly indicates the dependence of the pore water pressure to current density and resistivity of soil in electroosmotic process. At equilibrium, the current is the governing parameter in the process. If there is no current, the process will not occur, no matter how high the applied voltage, (Lo et al., 1991).

Eykholt (1997) presented theory for the development of non-uniform pore pressures during electroosmotic treatment caused by local deviations in the electric field intensity and soil chemistry. Consideration is made on a soil sample prepared in a rigid tube with free draining ends, with no initial excess pore pressure within the soil and no net hydraulic gradient. If an electric field is applied across the soil and if there are non uniformities in the local electric field intensity and/or surface chemistry, pore pressures will develop within the soil. Eykholt pointed that one important result by Esrig (1968) was that excess pore pressures (negative or positive) could be developed in an incompressible material during electroosmosis if the voltage drop was nonlinear, even if the boundaries were freely drained. Mise (1961) measured pore pressures in a saturated kaolinite with freely draining boundaries as low as -29 kPa. He suggested that the high negative pore pressures were due to an imbalance of pH in the soil (ranging from pH 2 to 12). He based this conclusion on his observations that the electroosmotic flow for kaolinite at pH 10 was nearly five times greater that of the flow for kaolinite at pH near 2. Sample pore pressure profiles from both Mise (1961) and Esrig (1968) are shown in Figure 2.6.

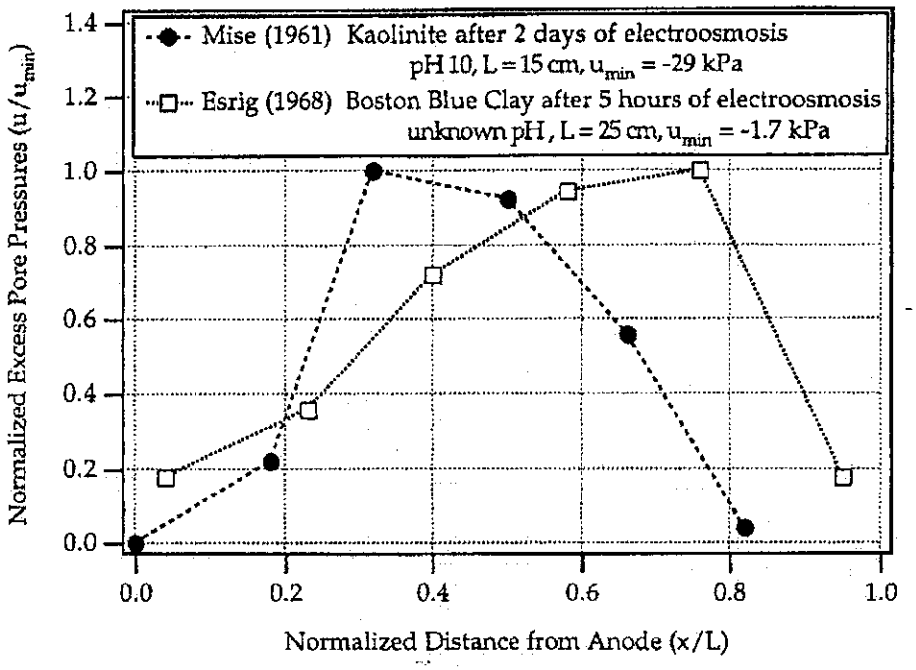


Figure 2.6 Sample of normalized excess pore pressure profiles (suctions) from electroosmosis experiments on freely drained clays (after Mise, 1961; and Esrig 1968)

2.1.3 Electroosmotic Consolidation

One of the method in which soil could be consolidated is applying a vertical load on the soil's surface. The applied vertical load or pressure can be due to the self weight of the soil structure or a surcharge load. When this load is applied to the soil, there will be a build up in the pore water pressure and the process of consolidation can be used to induce an additional effective pressure or to accelerate the dissipation of positive pore pressure. After the positive pore water pressure induced by the direct loading had dissipated, the electroosmosis continues to induce negative pore water, causing further consolidation. Thus, if electroosmotic action is required to stabilize the soil, the process could go on after all the excess positive water pressure has dissipated (Hamir, 1997).

The theory combining these two methods of consolidation was presented by Wan and Mitchell (1976) indicating that applying electroosmotic consolidation on top of vertical loading or surcharge results in a more rapid dissipation of excess pore water pressure. In

this discourse however, only theories pertaining to consolidation due to electroosmosis alone will be discussed.

Basically, the desired effect of electroosmosis is the removal of water from the soil mass which results in the consolidation and stabilization of the treated soil. Therefore the consolidation aspect of the process is also of special interest to many researchers. As previously explained for one-dimensional flow, the electrical and hydraulic contribution to fluid flow can be superimposed to yield the following equation;

$$\frac{\partial^2 y}{\partial x^2} + \frac{k_e}{k_h}\gamma_w \frac{\partial^2 V}{\partial x^2} = 0 \qquad (2.17)$$

For the particular boundary condition relevant to electroosmosis application, that is close anode and open cathode, the solution of equation (2.17) above is as given in equation (2.14) which is;

$$U_e = - \frac{k_e \gamma_w}{k_h} V$$

Thus, the magnitude of negative pore pressure that can be developed for consolidation is directly proportional to the voltage at any point and is dependant on the ratio of $\frac{k_e}{k_h}$ The higher the voltage V and the ratio $\frac{k_e}{k_h}$, the greater will be the consolidation pressure. It can also be observed that the finer-grained the soil, the smaller the k_h will be, whereas, k_e does not change significantly with decrease in particle size. Thus, for a given value of soil compressibility, the ultimate amount of consolidation that can be achieved using electroosmosis should be in highly plastic clay. It should be emphasized at this point that negative pore pressure generated in the soil causes consolidation in general to compressible clay or silt. In fine sand, the tensile stresses generated by the negative pore pressure are usually not adequate to cause densification of the soil skeleton. The process may result only in a temporary increase in strength due to the formation of capillary menisci. Cassagrande (1983) noted that electroosmosis has little or no effect on coarse sand; whereas Mitchell (1993) concluded that the soils deemed suitable for electroosmotic consolidation are fine grained materials including silts, clayed silt, and

silty clay. Shang and Ho (1998) found that settlement generated by electroosmosis was shown to be dependant on the preconsolidation pressure of the soil indicating that consolidation will be less effective in overconsolidated soil.

2.1.4 Rate of Consolidation

Esrig (1968) presented the theory of one dimensional electro-consolidation in a uniform field with constant voltage. This theory has been validated by Wan (1976), Lo et al., (1990) and Mitchell (1991). The equation for the development of negative pore pressure during electroosmotic consolidation is given by;

$$U_e = -\frac{k_e}{k_h}\gamma_w V(x) + \frac{2k_e\gamma_w V_M}{k\pi^2}\sum_{m=0}^{\infty}\frac{(-1)^m}{\left(m+\frac{1}{2}\right)^2}\sin\frac{\left(m+\frac{1}{2}\right)\pi x}{L}\left\{\exp-\left(m+\frac{1}{2}\right)^2\pi^2 T_v\right\} \qquad (2.18)$$

where $T_v = \dfrac{c_v t}{L^2}$ (2.19)

$$c_v = \frac{k_h}{m_v\gamma_w} \qquad (2.20)$$

and T_v = time factor

c_v = coefficient of consolidation

m_v = coefficient of volume compressibility

m = positive integer

the average degree of consolidation, $\overline{U}$;

$$\overline{U} = 1 - \frac{4}{\pi^3}\sum_{m=0}^{\infty}\frac{(-1)^m}{\left(m+\frac{1}{2}\right)^3}\exp-\left(m+\frac{1}{2}\right)^2\pi^2 T_v \qquad (2.21)$$

The solutions to equations (2.18) and (2.21) are shown in Figure 2.7 and Figure 2.8. They are applied in the same way as the theoretical solutions for classical consolidation theory (Mitchell, 1993).

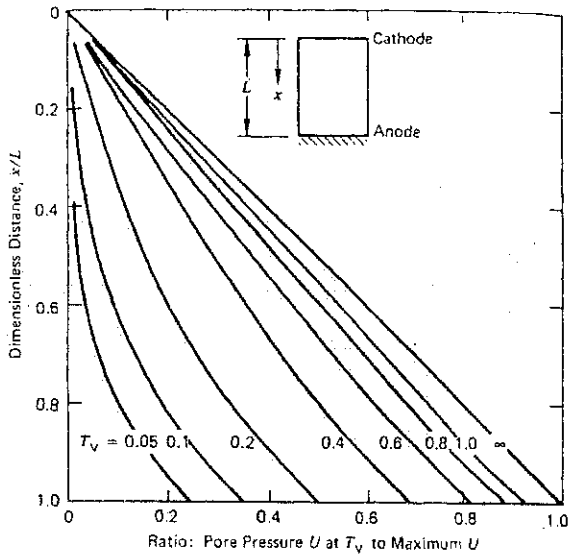


Figure 2.7 Dimensionless pore pressure as a function of dimensionless time parameter and distance for one dimensional consolidation using electroosmosis (after Esrig, 1968)

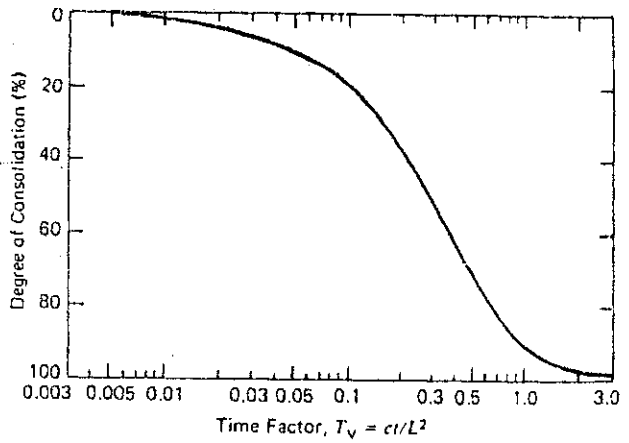


Figure 2.8 Average degree of consolidation versus time for one dimensional consolidation by electroosmosis (after Esrig, 1971)

By examining equation (2.18), three important conclusions can be drawn (Hamir, 1997);

i. When time = ∞, T_v is large and the pore pressure is given by the first term

$U_e = -\frac{k_e \gamma_w}{k_h} V$.

ii. The final negative pore water pressure at any point is the consolidation pressure at that point which is dependant on the ratio of $\frac{k_e}{k_h}$ and the voltage at that point. The higher the ratio of $\frac{k_e}{k_h}$ and the voltage *V(x)*, the greater will be the consolidation pressure.

iii. Electroosmotic permeability does not influence the rate of consolidation but only influences the magnitude of consolidation. This conclusion is arrive at by examining equation (2.18) which shows the development of pore pressure is dependant on T_v and T_v is dependant on c_v and $c_v = \frac{k_h}{m_v \gamma_w}$ which is independant of the electrokinetic permeability k_e.

Derivation of the theory above suggest that in reality electroosmotic consolidation behaves like ordinary consolidation under direct loading. The magnitude of the consolidation depends on the magnitude of the negative pore water that can be developed at the end of the consolidation process. Applying electroosmosis essentially develops negative pore pressure which acts like a surcharge load. By applying the principle of superposition in an already consolidating soil, using electroosmotic consolidation would simulate the application of an additional surcharge without the actual vertical load (Hamir, 1997).

2.1.5 Reverse polarity techniques

In the normal electroosmotic practice, the development of the pore water pressure is as such that maximum negative pore pressure occurs at anode and varies linearly to zero at

cathode. In other words, the non-uniform development of pore pressure along the sample consequently produces a non-uniform development of shear strength in the soil sample which might not be practical in actual field application. Reverse polarity could overcome these non-uniform pore pressure and shear strength problems by causing the soil near the cathode (now new anode) to consolidate and thus producing less variation in consolidation between the electrodes. Reverse polarity is also an effective technique in preventing dessication and decreasing electrode corrosion. It promotes a more uniform increase in the effective stress and improves the development of pore pressure (Gray and Samogyi, 1977; Shang et al., 1996). It also has the capability to increase the average current flowing through the soil (Shang et al., 1996).

During the process of polarity reversal, the voltage applied could be increased or decreased appropriately. The resulting negative pore pressure may then be calculated using the same equation (2.14) and this final negative pore pressure determines the magnitude of consolidation. Theoretical studies conducted by Wan and Mitchell (1976) indicate that a large gain in effective stress can be achieved in a relatively short time by doubling the applied voltage after polarity reversal. The effect of polarity reversal on the efficiency of the treatment was also studied by Shang et al. (1996). They concluded that the technique is viable for increasing the efficiency of the process. The increase in the efficiency is attributed to the reduction in the adverse electrochemical reaction which can occur during electroosmosis, such as changes in pH gradient and electrode corrosion (Hamir, 1997).

2.1.6 Previous field applications

There are reported instances, extending back to the 1930s, about the use of electroosmosis/electrokinetics to improve engineering characteristics of soil. These include attempts to dewater and stabilize soil, expedite the process of consolidation and improve the shear strength (Casagrande, 1951). It has been proven to be effective in stabilizing and consolidating soils both in the laboratory and in the field (Chappel and Burton, 1975; Mitchell and Wan, 1977; Shang et al., 1996; Shang and Ho, 1998). Other applications of electroosmotic treatment include improving stability of excavations

(Chappel and Burton, 1975); backfill strengthening and slope stabilization (Chappel and Huggins, 1998); and also electroosmotic treatment of piles (Soderman and Milligan, 1961; Naggar and Routledge, 2004). Many successful projects were reported in the literature, including the West Branch Dam, Mahoning River, Ohio (Fetzer, 1967); Kooteney Canal, British Columbia (Wade, 1976), Singapore Port (Chappel, 1975) etc.

Tables 2.2, 2.3, 2.4 and 2.5 summarize some of the case history of electroosmotic laboratory works and field applications covering various aspects of the treatment.

Table 2.2 Summary of some of the previous electroosmotic consolidation tests (after Hamir, 1997)

Author	Aims	Apparatus	Sample size	Parameters measured during test.			
				PWP Distribution	Settlement	Voltage distribution	Polarity reversal
Casagrande (1952)	To study the effect of electroosmosis on compressible fine grained soil.	Standard oedometer	Not described	No	Yes	No	No
Nicholls & Herbst (1967)	To study the radial drainage electro-osmotic consolidation process.	Fixed ring consolidometer	62.5 mm diameter.	No	Yes	No	No
Evan & Lewis (1970)	To study the effect of negative pore pressure on the effective stress and the shear strength of soil.	Insulated cylinder	38 mm diameter	At one electrode	No	No	No
Wan & Mitchell (1976)	To evaluate the stress-strain and strength changes caused by electroosmotic consolidation	Consolidation box	60x200x200 mm	Yes	Yes	Yes	Yes
Johnston & Butterfield (1977)	To study the development of pore pressure in electroosmotic consolidation.	Triaxial test	102 mm diameter	Yes	No	Yes	No
Lo (1991)	To investigate the electro-osmotic strengthening of soft sensitive clay.	Plexiglass tube	102x229 mm	Yes	Yes	Yes	Yes
Shang et al. (1996)	To study the effect of voltage gradient and reverse polarity on electro-osmotic consolidation	Triaxial cell	76 x 152 mm	Yes	Yes	Yes	Yes
Hamir (1997)	To study use of conductive geosynthetics as electrodes in electroosmotic consolidation.	Perspex tube consolidometer	150 x180 mm	Yes	Yes	Yes	Yes

Table 2.3 Summary of the electrical aspect of some of the previous laboratory work on electroosmotic consolidation (after Hamir, 1997)

Author	Electrodes	Applied voltage (Volts)	Voltage gradient (Volts/cm)	Current densities. (Amp/m^2)
Casagrande (1949)	Platinum wire gauze anode. Cotton fabric stretched over wire gauze as cathode	-	0.1 to 12	Not mentioned
Casagrande (1952)	Platinum wire mesh.	-	1.6	Not mentioned
Nicholls & Herbst (1967)	Steel nail in porcelain filter as cathode. Steel specimen ring as anode.	1.5,3.6	0.115, 0.572, 1.33	Not mentioned
Evan & Lewis (1970)	Platinum gauze.	1.5 to 2.0	-	-
Wan &Mitchell (1976)	Silver chloride with porous disk.	-	1.25	1.0 to 1.5
Johnston & Butterfield (1977)	Stainless steel mesh	3	0.3	-
Lo (1991)	Copper electrodes.	3 to 6	0.15 to 0.3	1.27 to 3.8
Shang et al. (1996)	porous copper disk		0.4 to 1.07	Not mentioned
Hamir (1997)	Conductive geosynthetics.	5 to 30	0.4 to 2.5	0.3 to 4.8

exchange). Longer term reactions are cementation and carbonation. An elaboration of the four reactions is given in the following paragraphs.

Hydration – A large amount of heat is released when quicklime (CaO) is mixed with clay. This is due to the hydration of quicklime along with the pore water of the soil. The increase in temperature can at times, be so high that the pore water starts to boil (Broms, 1984). An immediate reduction of natural water content occurs when quicklime is mixed with cohesive soil, as water is consumed in the hydration process.

$$CaO + H_2O \rightarrow Ca(OH)_2 + \text{Heat} \qquad (2.22)$$

The calcium hydroxide, $Ca(OH)_2$ from the hydration of quicklime or when using calcium hydroxide as the stabilizer, dissociates in the water, increasing the electrolytic concentration and the pH of the pore water, and dissolves the SiO_2 and Al_2O_3 from the clay particles.

$$Ca(OH)_2 \rightarrow Ca^{++} + 2(OH)^- \qquad (2.23)$$

These processes will result in ion exchange, flocculation, and pozzolanic reactions.

Ion exchange and flocculation – When lime is mixed with clay, sodium and other cations adsorbed to the clay mineral are exchanged with calcium. This change in cation complex affects the structural component of the clay mineral. Within a period of a couple of minutes up to some hours after mixing, the calcium hydroxide is transformed again due to the presence of carbonic acid (H_2CO_3) in the soil. The presence of carbonic acid in the soil is due to the reaction of carbon dioxide from the air in the soil and the free water. This reaction results in the dissociation of the lime into Ca^{2+} or Mg^{2+} and OH^- which modifies the electrical surface forces of the clay mineral and causes the clay to coagulate and flocculate. This change in soil structure is a consequence of cation exchange caused by the dissociated bivalent calcium ions in the pore water replacing such univalent alkali ions that are normally attracted to the negatively charged clay particles (Assarson et al., 1974).

$$Ca^{++} + \text{clay} \rightarrow Ca^{++} \text{ exchanged with monovalent ions } (K^+, Na^+) \qquad (2.24)$$

The order of replaceability of common cations associated with soils follows the lyotropic series (or Hofmeister series) as: $Na^{+} < K^{+} < Ca^{++} < Mg^{++}$, with highly metallic ions replacing the weaker one on the surface of clay particles. The crowding of Ca^{++} ions onto the surface of the clay particles (adsorption) brings about flocculation, Herrin and Mitchell, 1961 (cited from Bergado et al., 1996). Aydin (2004) stated that divalent exchangeable cations result in flocculated clay system while monovalent exchangeable cations produce dispersed system. Meanwhile, the ion exchange capacity highly depends on the pH of the soil water and the type of clay mineral in the soil.

Pozzolanic – When adequate quantities of lime and water are added, the pH of the soil quickly increases to above 10.5, which enables the clay particles to break down. Silica and alumina are replaced and react with calcium from the lime to form calcium-silicate-hydrates (CSH) and calcium-aluminate-hydrate (CAH). These compounds form the matrix that contributes to the strength of lime-stabilized soil. The gel of calcium silicate and/or aluminate hydrate cements to the soil particles in a manner similar to the effect produced by the hydration of Portland cement , but the lime cementing process is a much slower reaction which requires considerably longer time than the hydration of cement. The main part of the reaction does not start until a couple of days after the mixing of lime (Assarson et al., 1974). As a rule, it is not finish until one to five years later (Diamond and Kinter, 1965). The solubility of the pozzolan and thus their inclination to react with lime depends on the pH of the soil water. The rate of reaction also increases with increased soil temperature (Broms, 1984).

Carbonation – Lime reacts with calcium carbon dioxide in the atmosphere or in the soil to form relatively weak cementing agent, such as calcium carbonate or magnesium carbonate (Ingles and Metcalf, 1972). The strength of calcium carbonate which is formed by this process can be discounted, and its significance on the soil lime stabilization can be dismissed (Broms, 1984). Diamond and Kinter (1965) even suggested that carbonation is probably a deleterious rather than helpful phenomenon in the soil stabilization.

As mentioned earlier, effects of lime on clay resemble to some degree the effects of chemical stabilizer introduced in electrokinetic stabilization method. It is therefore necessary to look into some of the factors affecting lime stabilization to further have a preliminary understanding of the behaviour of stabilizer induced electrokinetic treatment, and later to compare the different aspects of both the stabilization methods mentioned above.

2.2.2 Predominant factor controlling hardening characteristics of lime treated clay

i. Type of lime – The efficiency of lime stabilization depends partly on the type of lime material used. Quicklime is in general more effective than hydrated lime. Quicklime will result in the absorption of water from the soil and more importantly, the hydration will cause an increase in temperature which is favourable to strength gain.

ii. Lime content – In general, the strength of soil when added with lime increases as the lime content increased. Herrin and Mitchell, 1961 (cited from Bergado et al, 1996) denote that there appears to be no optimum lime content which produces a maximum strength of the soil under all conditions. However, it can be stated that for a particular conditions of curing time and soil type, there is a corresponding optimum lime content which causes the maximum strength increase.

When lime is added to a clay soils it must first satisfy the affinity of the soil for lime, that is, ions are adsorbed by clay minerals and are not available for pozzolanic reactions until this affinity is satisfied. Because the lime is fixed in the soil and is not available for other reaction, the process has been regarded as lime fixation (Hilt and Davidson, 1960). This lime fixation point corresponds with the point where further addition of lime does not bring about further changes in the plastic limit. This therefore is the optimum addition of lime needed for maximum modification of the soil and is normally between 1% and 3% lime added by weight. Beyond this point, lime is available to increase the strength of soil which is the stabilizing part of the process.

Ingles and Metcalf (1972) suggested the addition of up to 3% of lime would modify silty clays, heavy clays and very heavy clays, while 3-4% was required for the stabilization of silty clay, and 3-8% was proposed for stabilization of heavy and very heavy clays. They

suggested that a useful guide is to allow 1% of lime (by weight of dry soil) for each 10% of clay in the soil. Eades and Grim (1966) suggested that the amount of lime consumed by a soil after one hour affords a quick method of determining the percentage of lime required for stabilization, i.e. the lowest percentage of lime required to maintain a pH of 12.6 is the percentage of lime required to stabilize the soil. Hilt and Davidson (1960) gave a correlation which showed that the amount of lime fixation is in proportion to the type and amount of clay present and is independent of the adsorbed cation present in the clays. The relationship is given as;

$$Optimum\ Lime\ Content = \frac{\%\ of\ clay}{35} + 1.25 \qquad (2.25)$$

Bell (1996) noted that expansive clays respond more quickly to strength increase. For instance, montmorillonite showed a rapid initial increase in unconfined compressive strength with small additions of lime and excessive addition of lime reduces strength (Figure 2.11). This is due to the fact that lime itself has neither appreciable friction nor cohesion. The addition of small amount of lime to kaolinite and quartz also give rise to notable increase in unconfined compressive strength (Figures 2.12 and 2.13).

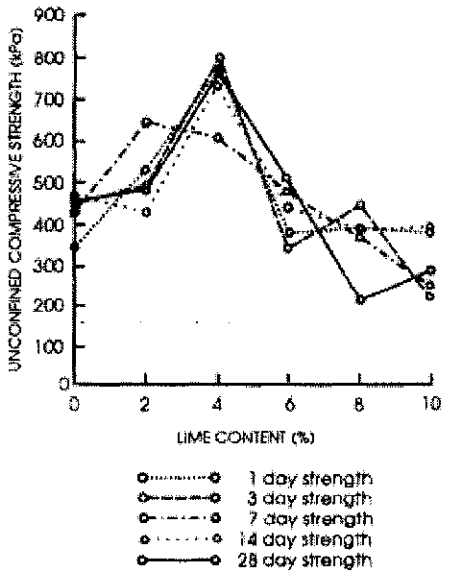


Figure 2.11 Unconfined compressive strength of montmorillonite with various additions of lime (after Bell, 1996)

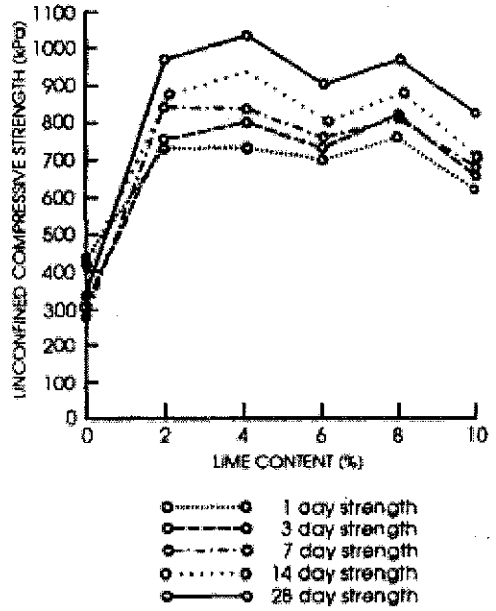


Figure 2.12 Unconfined compressive strength of kaolinite with various additions of lime (after Bell, 1996)

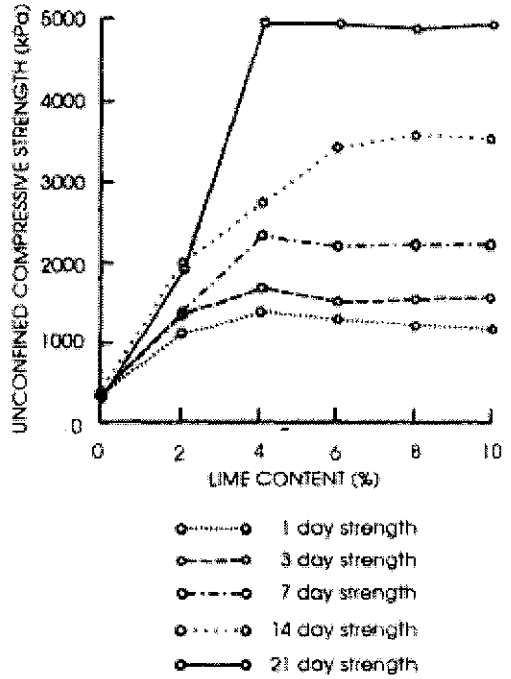


Figure 2.13 Unconfined compressive strength of quartz with various addition of lime (after Bell, 1996)

iii. Curing time – Among the different variables affecting the strength of lime stabilized clay soil, curing time is of major importance. Its effect on strength is a function of time, temperature and relative humidity (Mitchell and Hooper, 1961). The shear strength of the stabilized soil gradually increases with time through pozzolanic reactions when the lime reacts with the silicates and aluminates in the soil, Broms, 1984 (cited from Bergado et al., 1996). The rate of increase is generally rapid at the early stage of curing time and thereafter, the rate of increase in strength decreases with time. Lime has an initial reaction with soil, taking place during the first 48-72 hours after mixing, and a secondary reaction which starts after this period and continues indifinitely (Taylor and Arman, 1960). Bell suggested that the strength increases rapidly at first, generally during the first 7 days of curing, then increases more slowly at a more or less constant rate. Figure 2.14 shows a typical plot of the increase of shear strength with time for various types of soils.

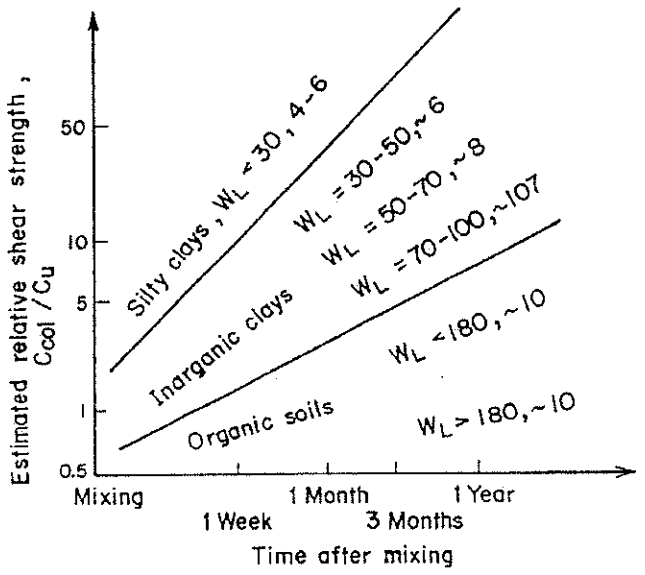


Figure 2.14 Increase of shear strength with time (after Broms, 1984)

iv. Type of soil – For the lime treatment to be successful, the clay content of the soil should not be less than 20% and the sum of the silt and clay fractions should preferably exceed 35%, which is normally the case when the plasticity index of the soil is larger

than 10%, Broms, 1984 (cited from Bergado et al., 1996). The shear strength increase of the stabilized soil is highly dependant on pozzolanic reactions, i.e., the reaction of lime with the silicates and aluminates in the soil. The increase with time is in general highest for normally consolidated silty clays with low plasticity index and a low water content. The strength increase in lime treated organic soils is often very low, even a relatively small amount of organic material can have a large effect on the strength increase (Broms, 1984). Gypsum has been used together with unslaked lime to stabilize organic soils when lime alone is not effective (Broms and Anttikoski, 1983). Generally, the effect of lime decreases with increasing water content (Holm et al., 1983; Miura et al., 1987). Figure 2.15 shows the effect of grain size distribution on the lime stabilization method.

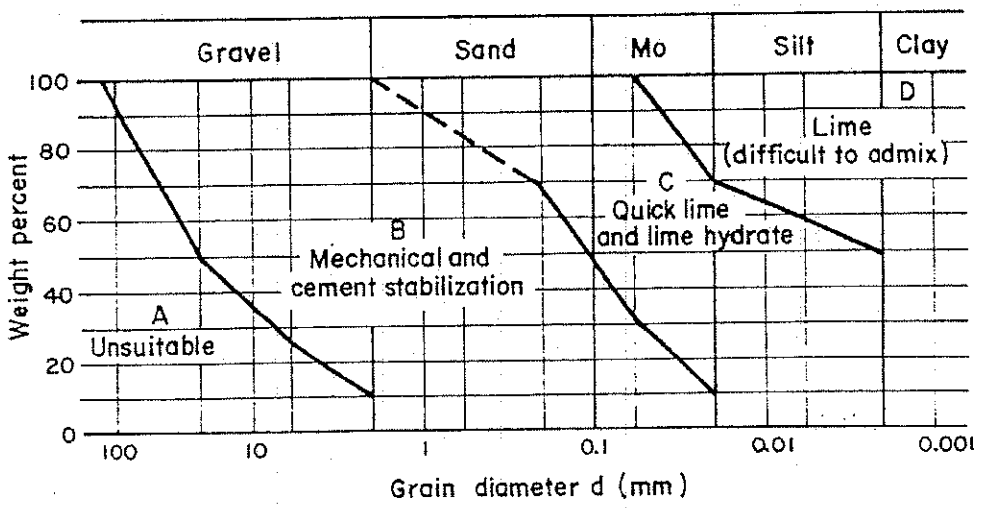


Figure 2.15 Effect of grain size distribution on the applicability of lime stabilization (after Kezdi, 1979)

v. Clay minerals – Clay soils have a wide range of mineralogical composition. They may consist of various proportions of different types of clay minerals, notably kaolinite, illite, mixed-layer clays and montmorillonite. Clay soils also might consist of non-clay minerals, notably quartz, and/or organic matter and colloidal matter. Eades and Grin (1966) reported that the quantity of lime needed to effectively treat soil is dependant on

the type of clay mineral present. Bell (1988) observed that the strength of soil-lime mixtures depends of several factors including the soil type (clay minerals) and the type and amount of lime added. Eades and Grim (1966) again observed that although kaolinites, illites, montmorillonites and other mixed-layered clays all react with lime to give greater strengths, the quantity of lime needed to treat clay is dependant on the type of mineral present.

Expansive clay minerals such as montmorillonite exhibit a high cation exchange capacity, whereas non-expansive clay minerals like kaolinite have a relatively low cation exchange capacity (CEC). Bell (1996) conducted experiments to determine the CEC of kaolinite and montmorillonite using different percentage of lime addition. Although results show different percentage of lime produces different CEC, there was little relationship between the changes of CEC with the development of strength supporting that cation exchange capacity is not an important factor in terms of strength development when lime is added to these clay minerals. However one should keep in mind that cation exchange capacity is a very important factor in clay mineralogy and a big contributor as far as lime modification is concerned.

Hilt and Davidson (1960) found that from the unconfined compression test results, kaolinite and montmorillonite clayey soils are effectively stabilized with lime alone whereas illitic clays require addition of fly-ash to obtain a significant strength gain. Montmorillonite clays give lower strengths with dolomitic limes than with high calcium or semi-hydraulic limes (Bell, 1988). Kaolinitic clays, on the other hand, yield the highest strengths when mixed with semi-hydraulic limes and the lowest strength are obtained with high-calcium limes. Lee et al., (1982) found that in terms of strength increase, lime treatment has a greater effect in montmorillonites than kaolinite soils.

vi. Soil pH – Addition of lime will also raise the pH of the soil, which in turn increases the cation exchange capacity. As explained earlier, cation exchange process results in the flocculation and agglomeration of clay particles. The rise in pH of the pore water increases the solubility and reactivity of silica and alumina (pozzolans) present in the clay particles (Bergado et al., 1996). Lime also provides free calcium that combines

with pozzolans present in the clay to form more calcium silicate hydrates and calcium aluminate hydrates. This reaction is called pozzolanic reaction (Little, 1995).

When adequate quantities of lime and water are added, the pH of the soils quickly increases to above 10.5, which enables the clay particles to break down. Silica and alumina are released and react with calcium from lime to form calcium-silicate-hydrates (CSH) and calcium-aluminate-hydrates (CAH). These compounds form the matrix that contributes to the strength of lime stabilized soil. Therefore the ability to dissolve the SiO_2 and Al_2O_3 from the clay particle surface is of prime importance in the hardening of lime treated soil and this ability depends on the pH of the water content in the soil. Broms (1984) stated that the long term chemical reactions in lime stabilized soils are favored by a high pH value (pH>12) since the reactions are accelerated due to increased solubility of the silicates and aluminates (pozzolans) present in the clay. Davidson et al., (1965) suggested that a minimum pH of approximately 10.5 is necessary for pozzolanic reaction to take place, while Eades and Grim (1966) suggested that the lowest percentage of lime required to maintain a pH of 12.4 is the percentage required to stabilize a soil. Broms (1984) pointed out that the pH of the treated soil will normally exceed 12 even when only a few percent of lime has been added to the soil.

vii. Curing temperature – The chemical reactions in the soil are favoured by a high temperature. Curing temperature is another factor influencing strength of lime stabilised soil (Bell and Couthard, 1990). Higher temperatures accelerate curing, and this gives rise to higher strength as shown in Figure 2.16.

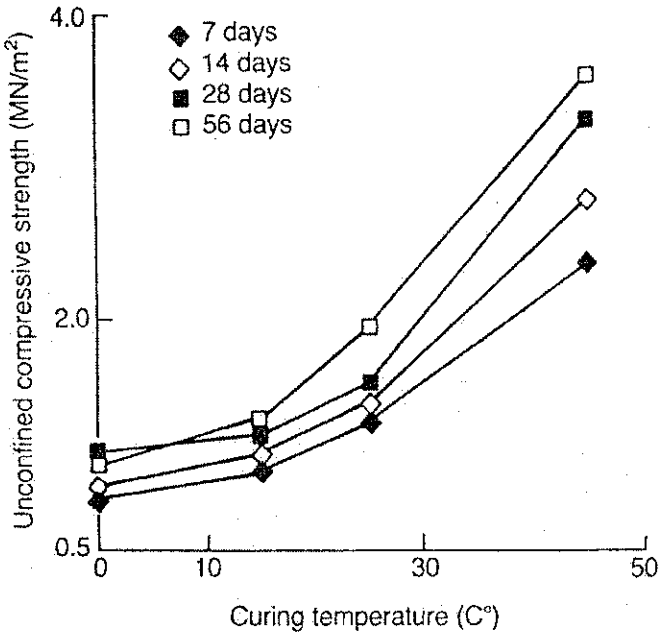


Figure 2.16 Influence of curing temperature and time on strength of clay of very high plasticity stabilized with 5% addition of lime (after Bell, 1992)

The soil-lime reaction will normally retard and may cease once temperature falls below 4°C. Broms (1984) attributed the favourable effects of high curing temperature to the increased solubility of the silicates and aluminates in the clay at high temperatures. Metcalf (1964) found that for lime stabilized clays, the curves of unconfined strength versus temperature were different for different clays, and there was an abrupt change in slope in the vicinity of 45°C. Chaudry (1966) reported that the compacted lime stabilized Bangkok clay cured at 100°F had higher strength values than those cured at 70°F.

viii. Natural water content – The strength of lime stabilized soils decrease with increasing moisture content (Bell, 1988). Figure 2.17 shows that even three months after stabilization, the shear strength of soils with high saturated moisture contents remain low. On the other hand, soil-lime mixtures compacted at moisture contents above optimum, after brief period of curing, attain high strength than those compacted with moisture content less than optimum. This is probably because the lime is more uniformly diffused and occurs in a more homogeneous curing environment.

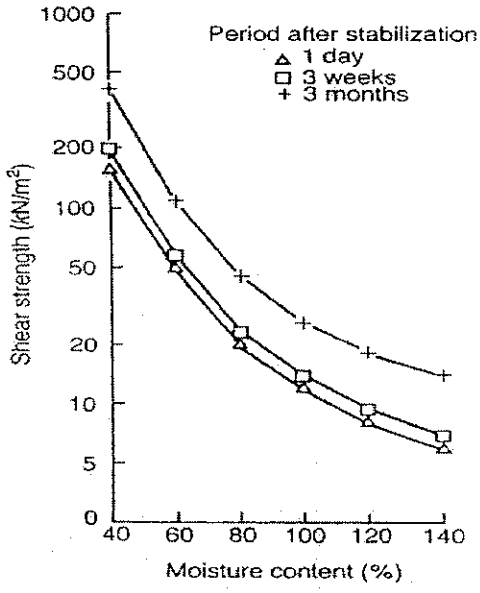


Figure 2.17 Variation of shear strength with increasing moisture content (after Bell, 1992)

2.3 Electrochemical stabilization of soil

Conventional chemical stabilization method without using electrical current has many limitations especially in deep stabilization covering large area. In many cases, the main problem is to transport chemical species into clays due to their low hydraulic conductivity if the normal injection method is used.

Somehow, it has been unexpectedly discovered that by running electrical current using electrodes and with the addition of suitable electrolytes either at the anode, or cathode or both anode and cathode, greatly facilitates the transport of desired ions through the soil. This will enhance the process of stabilizing the soil especially through cementing reactions. Using the technique of this invention, ionic species can be transported through soil at rates of several centimeters a day or more even in soils such as clays having a low hydraulic permeability. With this electrochemical stabilization technique, deep stabilization for the entire area is possible for both flat ground and slope conditions. For example, lime stabilization for slope condition could be done as previously described in Figure 2.9 and 2.10. Utilizing the electrochemical method, the same lime free ions will travel throughout the soil mass and react with the soil particles resulting in both modification and stabilization of the entire soil mass as shown in Figure 2.18. In addition,

this technique treats soils without excavation, an advantage over traditional mix-in-place chemical stabilization. It is reported that this technique is particularly well suited to soils of low permeability for which injection of stabilizing agents by hydraulic means is impractical.

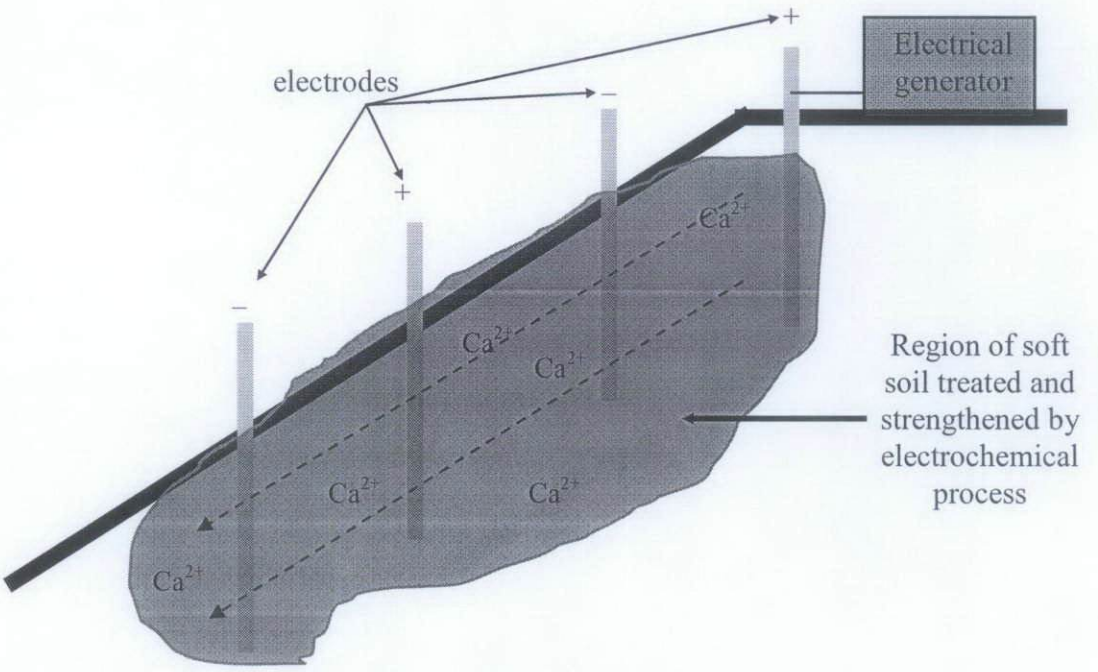


Figure 2.18 Electrochemical stabilization in slopes

2.3.1 Mechanism of electrochemical stabilization

Whereas the chief mechanism of improvement achieved by electroosmosis is reduction in water content, electrochemical stabilization is employed in an effort to improve the soil properties through modification and stabilization reactions very much like what we have in the traditional chemical stabilization. The advantage of electrochemical stabilization over the normal non-electrokinetic method as discussed earlier is that it greatly facilitates the transport of 'desired ions' through the soil enhancing the ability to strengthen the soil through both modification and especially stabilization through cementing process. It is a technique of ground improvement in which stabilizing agents are induced into the soil under DC electrical fields. Cationic species are injected at the anode, and anionic species at the cathode with suitable electrolyte conditioning. If acid or base formation in the soil

negatively affects transport, chemical conditioning is used to neutralize the acid or base products of electrolysis.

Adamson (1965) observed that the degree of soil stabilization and course of the process are dependant on clay content, types of clay present, the concentration of salts in the soil solution, soil temperature increase during passage of current through the soil and types of chemical added to the soil. Another important factor contributing to the stabilization is the type of electrodes used. The movement of stabilizing agents into the soil masses is governed by the principle of electrokinetics, while the mechanism of stabilization can be explained by the principles of chemical stabilization (Baker et al. 2004).

The two main mechanisms in electrochemical enhancement are;

Modification – Basic concepts were given in the lime stabilization section 2.2.1. In addition to what was mentioned, studies of clay mineralogy show that the properties of clay are greatly influenced by the surface forces. These surfaces are negatively charged, primarily as a result of the isomorphous substitution of aluminium or silicon atoms by the lower–valency atoms. This negative charge attracts dipolar water molecules, resulting in the clay particles being surrounded by the diffuse double layer. The concentration of cations available in the pore water and the surface charge of the clay particles together control the thickness of this layer. In addition, the pH of the system can influence the negative charge of the clay particles. In some cases (e.g. kaolinite) significantly, and therefore directly influence the thickness of the diffuse layer.

The cations commonly found in the diffuse double water layer and the pore water are variously sodium, potassium, calcium, magnesium and lithium, and in some cases higher order ions are also present (Little, 1987). When cations of a higher valency and/or a larger ionic radius, such as calcium, silicon or aluminium are introduced in significant concentrations, they saturate the solution and become adsorbed at the clay surface in preference to those ions originally present.

The result of this cation exchange, due for example to the classic case of lime (and hence calcium ion) addition, is a considerable reduction in the thickness of diffused water layer, as illustrated in Figure 2.19. This allows closer contact between the clay platelets, which

promotes edge-to-edge attraction, or flocculation, and results in changes in the soils workability, permeability, plasticity and swell properties.

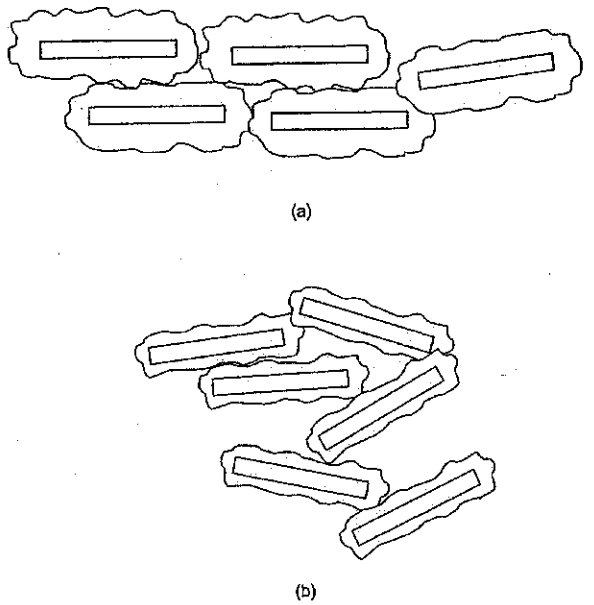


Figure 2.19 Flocculation of clay platelets (after Little, 1987): (a) parallel arrangement of clay particles with hydrated water layers; (b) edge-to-edge attraction induced by thin water layer, which allows attractive forces to dominate

Stabilization – This process could be divided into two aspects;

i. Cementation - alteration of the soil pH during electrochemical process results in changes in the solubility of the clay minerals present. Stabilizing agent such as calcium chloride induced in the soil results in a high pH environment. This high pH environment will then dissolve some of the SiO_2 and Al_2O_3 from the clay particles much like what happen in the traditional lime stabilization. The Ca^{2+} ions from the stabilizing agent react with the dissolved SiO_2 and Al_2O_3 under this high alkaline condition (usually more than pH 10) producing a pozzolanic reaction and leads to the formation of cementing agents, consisting of calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH).

$$Ca^{++} + 2(OH)^{-} + SiO_2 \rightarrow CSH \qquad (2.26)$$

$$Ca^{++} + 2(OH)^{-} + Al_2O_3 \rightarrow CAH \qquad (2.27)$$

ii. Precipitation – when different ionic species in the pore fluid migrate from anode to cathode or from cathode to anode, this will result in the precipitation of some of the ions in the soil. Precipitation occurs when an ion from one solution comes in contact with an ion from the second solution to form crystals of an insoluble salts. For example, when phosphoric acid is used in a certain electrochemical treatment of soils, phosphate precipitates will be formed, contributing to the increase of shear strength in the soil. In certain electrokinetic strengthening of soil, it is precipitation that provides the greatest contribution of strength, especially where the pH value of the soil is greater than 7.

2.3.2 Some aspects of electrokinetic/electrochemical transport and its complexities

It is necessary to first present the governing principles and boundary conditions used for applying DC electrical field in electrokinetic/electrochemical stabilization. The main component for general electrochemically based treatment systems are the soil, the electrolytes used or injected at the electrodes, and the electrodes used to apply DC current. While these components are similar in most application, the changes in their types (such as amendments, electrolytes or electrodes) vary depending upon the type of application (Alshawabkeh et al. 2004).

Alshawabkeh and Acar, 1996 presented several equations under simplifying assumptions to calculate the material fluxes that develop in soils under coupled gradients. The simplified assumptions are;

i. The porous medium is isotropic and saturated.
ii. Isothermal conditions prevail (coupled heat transfer is neglected).
iii. All the applied voltage is effective in fluid and charge transport (no losses at the electrodes).
iv. Electrophoresis is not present.
v. Chemico-osmotic and ion filtration coupling are negligible.
vi. Soil particles are treated as electrically nonconductance (insulators).

vii. Surface conductance and streaming potential are negligible.

The equations and types of material fluxes or flow are given as follows:

- total fluid flow (q) under hydraulic (Darcy's law) and electric (electroosmotic) gradients, governed by the combined expression

$$q = -k_h \frac{\partial h}{\partial x} - k_e \frac{\partial \phi}{\partial x} \tag{2.28}$$

- total mass flow (J_i) of chemical species, i, under concentration gradients (Fick's law), electric gradient (ion migration) and advective fluid flux is given by

$$J_i = -D_i^* \frac{\partial c_i}{\partial x} - u_i^* c_i \frac{\partial \phi}{\partial x} + q c_i \tag{2.29}$$

- charge (ions) flow under electric (Ohm's law) and concentration gradients, given by

$$I = -\sigma^* \frac{\partial \phi}{\partial x} - \sum F D_i^* \frac{\partial c_i}{\partial x} \tag{2.30}$$

$$\sigma = F \sum z_i u_i^* c_i \tag{2.31}$$

where q = fluid flux per unit area due to hydraulic gradient ($L^3T^{-1}L^{-2}$)

k_h = hydraulic conductivity (LT^{-1})

h = hydraulic head (L)

k_e = coefficient of electroomotic permeability ($L^2V^{-1}T^{-1}$)

x = longitudinal distance (L)

I = electric current density (AL^{-2})

ϕ = electric potential (V)

J_i = diffusion mass flux of species i per unit area ($MT^{-1}L^{-2}$)

D_i^* = effective diffusion coefficient (L^2T^{-1}) of species i

u_i^* = effective ionic mobility of ion ($L^2V^{-1}T^{-1}$)

F = Faraday's constant

c_i = concentration of chemical species (ML^{-3})

σ^* = effective electrical conductivity (SL^{-1})

z_i = charge of ion i

Possible boundary conditions for the fluxes consist of:

i. fluid drainage conditions (flow or no flow)
ii. electrical conditions including the intensity and variability of the applied DC field
iii. chemical condition at each boundary (e.g. chemical concentration of available electrolyte)

The desired combination of these boundary conditions depends on the type of application. For example, an impermeable flow boundary is used at the anode in electroosmotic consolidation (Cassagrande, 1952), a low pH boundary is used at the cathode in the extraction of heavy metals (Acar and Alshawabkeh, 1993), and a constant concentration of ionic grout/chemical is used at the cathode in ionic grouting of soils (Alshawabkeh and Sheahan, 2003). The boundary conditions are clearly a strong determinant of the system's effectiveness to achieve a particular goal since they are the only controllable inputs to the system (Alshawabkeh et al., 2004).

Equation 2.29 and 2.30 are the bases for injection of chemical stabilizers (ionic injection) to stabilize soft soils. These equations describe how electroosmotic flow and/or ionic migration (as in electrochemical treatment) can be used for injecting chemical grouts/stabilizers through low permeability soils. As mentioned earlier, this electrokinetic/electrochemical technique are different than electroosmotic consolidation in that the transport process are utilized for injecting chemical agents into the soil. While electroosmosis mobilizes the pore fluid, carrying soluble grouts/stabilizers towards the cathode, ionic migration (due to electrochemical process) effectively transports negative anions to the positive anode and positive cations to the negative cathode. The important difference is that this mode of chemical transport can potentially occur even without any fluid flow, compared to the use of electroosmosis to induce chemical transport (Gray and Mitchell, 1967).

For example, when anions and cations are placed in the vicinity of the anode, cations are transported from the anode to the cathode both by electroosmosis and electromigration

(electrochemical). Because the directions of both transport mechanisms are the same (i.e. from anode to cathode), cation transport from anode to cathode transport is enhanced by the combined effects of both electroosmosis and electromigration. By contrast, for anions, the direction of transport by electromigration is from cathode to the anode, while electroosmotic transport will be from the anode to the cathode. Because the electroosmotic transport rate is less than the transport rate by electromigration, anions placed in the anode compartment will only travel toward the anode relatively slow. Cations move in the porous media move towards the cathode, and anions within the porous media move towards the anode by electromigration to preserve electrical neutrality.

Similarly, when chemical species are placed in the vicinity of the cathode, anions tend to move from the cathode towards the anode by electromigration, while electroosmotic transport acts against such transport. However, anions are still transported efficiently from the cathode towards the anode because again the transport rate by electroosmosis is in general lower than the transport rate by electromigration. Futhermore, electrosomotic transport can be minimized by appropriate conditioning of the pore fluid. For example, placement of chemical conditioners with smaller cations at the anode compartment and larger anions at the cathode compartment, or increasing the ion content of the pore fluid (e.g. by acidification) can help minimize electroosmotic transport and any of its adverse effects on species transport. The cations and anions used are preferably selected to form strengthening mechanism – ions exchanges, pozzolanic effects and precipitates. Thus when cationic species are injected at the anode and anionic species injected at the cathode, or it may be just either cations or anions injected to just one electrode, strengthening reactions can prevail in the soil as the result of cross-transport of species.

The above mentioned explaination is an attempt to explain the comparison on the effect of electroosmosis and electrochemical methods in soil stabilization. In many cases, with regard to electrochemical method to stabilize soils, electroosmotic transfer of water inevitably accompanies the process. This is in general, is the desired case whereby electrochemical treatment will actually remove the pore water and hence causing consolidation and at the same time results in ionic migration improving the strength and

characteristics of the soil by the three previously mentioned mechanisms, namely cation replacement, mineralization/cementation and precipitation of species in the pore fluid.

2.3.3 Predominant factors controlling the strengthening characteristics of soil in electrochemical process.

The basic predominant factors controlling the improvement/strengthening of soil in electrochemical process resembles that of lime stabilization and electroosmotic stabilization and were outlined in the previous section. In summary, there are given as follows;

i. Type of chemical
ii. Chemical content
iii. Period of treatment
iv. Type of soil
v. Clay minerals
vi. Soil pH
vii. Temperature changes during treatment
viii. Natural water content
ix. Type of electrodes
x. Arrangement of electrodes

All the factors given above have to some extent being elaborated in previous sections concerning on electroosmotic and traditional chemical/lime stabilization. The following sections will however further touches on some factors which the author feels requires supplementary discussions so as to bring about a better understanding of the subject matter. Those factors are;

i. Type of chemicals injected.
ii. Types of soils, clay mineral and sizes of particle/grain.
iii. Types and arrangement of electrodes.

i. Type of chemical injected

The degree of stabilization and course of the process are dependant on clay content, types of clay present, the concentration of salts in the soil solution, soil temperature increase during the passage of current through the soil and types of chemical added to soil. Calcium chloride, aluminium acetate, and aluminium sulfate have proven to be quite effective in increasing shear strength (due to cementation) and decreasing swelling characteristic due to base exchange (Adamson et al., 1965). Therefore the types of chemical added/injected will determine the type of cationic and ionic species that will penetrate into the soil enhancing the ability of electrokinetic process to stabilize the soil through especially cementing reactions. This process of choosing the right or suitable chemical injected through the appropriate electrodes is also known as electrolyte conditioning, where the desired cations and anions are preferably selected to form cementitious precipitates in the soil. Thus when cationic species are injected at the anode, and anionic species injected at the cathode, stabilization reactions can prevail in the soil as a result of cross transport of species, and a homogenous, uniform cementation and stabilization can be achieved in a short time.

For example, to neutralize acid formed at the anode and the hydrogen ions that can interfere with cation transport, basic electrolytes containing the desired cations may be introduced at the anode. Such electrolytes for example might contain one or more of $Ca(OH)_2$, $Mg(OH)_2$, NaOH, KOH or $Al(OH)_3$. With competing H^+ ions neutralized by the introduced OH^- anions, the desired cations will travel by ionic migration, electroosmosis, or advection, allowing them better to be used in soil stabilization after transport.

In the normal method of electrokinetic stabilization, a non-uniform strength improvement is normally obtained after treatment. The quality of improvement decreases from the cathode to the anode. This is because when cations are used as stability agents, ions migrate into soils through the processes of electromigration and osmotic advection as mentioned before. These ions improve the soil strength by three mechanisms, namely cation replacement, mineralization and precipitation of species in the pore fluid. Precipitation and mineralization provides the greatest contribution in increasing the

strength. However, this type of reaction usually occurs when pH values of the soil solution are greater than 7. Therefore, the pH values of the soil solution need to be maintained above 7 during treatment in order to maximize its efficiency.

The technique of neutralizing acid formed in the soil is oftenly called the depolarization technique. This technique prevents the formation and thus migration of the hydrogen ions (which hinder the stabilization process) into the soils. To understand this concept better, a schematic representation of both the non depolarization and depolarization methods are given in Figure 2.20 below.

Asavadorndeja and Glawe (2004) used this depolarization method to experimentally stabilize soft Bangkok Clay using $CaCl_2$ solution of pH 10 and after 7 days of treatment, the shear strength had increased between 500% and 600% covering almost the entire soil specimen.

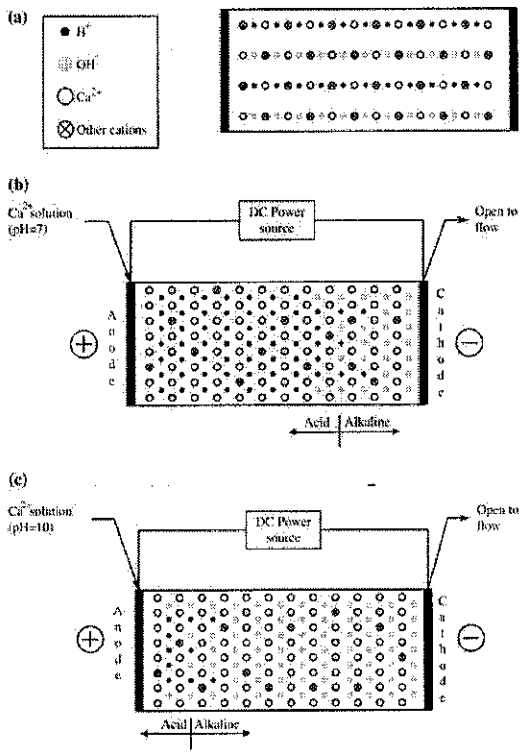


Figure 2.20 Schematic of principle of electrokinetic stabilization (a) initial condition (b) results from electrochemical stabilization without depolarization technique (c) results from electrochemical stabilization with depolarization technique (after Asavadorndeja and Glawe, 2005)

The examples briefly cited above are cases where acid are neutralized at the anode. Another example is to neutralize base formed at the cathode and the hydroxyl ions that can interfere with anion transport, where acidic electrolytes containing the desired anions may be introduced at the cathode. For example, such electrolytes might contain one or more of H_2SO_4, H_3PO_4, H_2CO_3, H_2SiO_3 or H_2SiF_6 (although H_2SiO_3 is insoluble in water, it could still be useful as a dry powder added as a depolarizer). In some cases, both of the above techniques are used, that is conditioning of the electrolyte at both the anode and the cathode. The two processes may run simultaneously or sequentially.

In one of the many treatment conducted, the soil is saturated with a cation such as Ca^{2+} introduced at the anode in the presence of OH^-, and the cation migrates through the soil until it reaches the vicinity of the cathode compartment. Then a solution containing an anion such as SO_4^{2-} is introduced at the cathode in the presence of H^+, and the anion migrates through the soil and reacts with the cationic species to cause cementing reactions with the soil. In the past and recent years, many researchers had adapted the electrolyte condition concept by using different electrolyte at either anode or cathode or both.

Adamson et al., (1966) for example introduced calcium chloride at one end of the soil sample and then after it had migrated through the whole sample, the polarity was reversed and saturated aluminium sulfate solution was introduced at the other end in which results show the possibility of strengthening the treated soil by electrochemical method using different electrolyte combination.

Thomas and Lentz (1990) ran series of experiments on kaolinite soil using phosphoric acid in the first series and only water in the second. It was observed that the soil strength and characteristics were significantly improved in the treatment using phosphoric acid if compared with the one with only distilled water. They discovered that the addition of phosphoric acid near the cathode produced a type of force imbalance in the electrochemistry by providing a virtually unlimited source of hydrogen ions so that the soil pH never become basic.

Harton et al. (1967) introduced 4000 cm^3 solution of calcium chloride followed by 1000 cm^3 solution of aluminium sulfate on samples of clayey silt. The areas nearest both to anode and cathode showed substantial increase in degree of stabilization.

In stabilizing kaolinite soil, Ozkan et al. (1998) employed electrochemical treatment to simultaneously inject phosphoric acid at both the anode and cathode in the first test (Test 1). In the second test (Test 2), aluminium ions were injected through the anode using aluminium sulphate and phosphoric acid at the cathode. Both tests exhibit strength improvement. In the phosphoric acid treatment, the strength increase in kaolinite was mainly contributed by ion exchange reactions, ion adsorbtion and fabric changes. In aluminium sulphate and phosphoric acid treatment, besides the reaction that occurred in Test 1, the strengthening effect was also contributed from the formation of insoluble phosphate compounds especially aluminium phosphate.

Alshawabkeh and Sheahan (2003), compare the usage of nitric acid and phosphoric acid in stabilizing clay soil. The results show that shear strength increases of up to 560% of the soil's baseline strength can be achieved by adding phosphoric acid, whereas little strength increase resulted from the nitric acid addition. Phosphoric acid addition at the cathode produces very little reverse osmosis flow whereas test with nitric acid addition at the cathode showed a significant and constant reverse flow. Studies from the results suggest that, when nitric acid was used, soil acidification (due to electrolysis at the anode) was enough to reverse the polarity of the clay surface charge and consequently reverse the electroosmotic flow. However, the drop in the surface charge due to acidification was not enough to reverse the electroosmotic flow in the phosphoric acid case. The immediate impact of nitric acid at the cathode seems to be the reason for the reverse flow. The difference between the nitric and phosphoric acid cases may be related to the changed in the electrical conductivity of the pore fluid.

Kassim et al. (2003) employed three different anolyte-catholyte combinations in the electrochemical treatment on a residual tropical soil, namely distilled water-distilled water, $CaCl_2$-distilled water and distilled water-H_3PO_4 combination. Results among others showed that the introduction of 1.0M H_3PO_4 at the cathode yielded high voltage gradients due to the formation of phosphate compounds in the soil. The introduction of

1.0M $CaCl_2$ at the anode produced high current densities because the calcium remains ionic due to the acidic environment within the soil mass.

ii. Types of soils, clay minerals, and particle/grain sizes

In general the three common clay minerals are kaolinite, illite, and montmorillonite. A major difference in the chemical structures of these clay minerals is the bonding between the clay layers. Although kaolinite is neutral, it is a polar structure with layers held together by hydrogen bonds; thus, kaolinite is a stable structure unlikely to shrink and swell. Isomorphous substitution in the formation of both illite and montmorillonite creates a positive charge deficiency while exchangeable cations and water are attracted between the clay layers to balance the charge deficiency. The strength of these bonds and interlayer spacing depend on which exchangeable cations are present and the availability of water. These bonds are generally weaker and less stable than those of kaolinite, resulting in a greater potential for shrink and swell (Thomas and Lentz, 1990). At this point, it is important to reiterate that the properties of a clay and its effectiveness in electrokinetic/electrochemical treatment are therefore greatly influenced by the surface forces. The pH of the system can influence the negative charge of the clay particles in some cases (e.g. kaolinite) significantly, and thereupon directly influence the thickness of this diffuse double layer.

Among the physical factors influencing in any electrokinetic/electrochemical process are the grain size and soil/mineral type. Electrokinetic/electrochemical method works more efficiently in fine-grained materials where the surface properties of particles are dominant. Typically, electrokinetic/electrochemical become predominant in systems where 30% or more of particles are finer than 2 μm. Experiments also indicate that among different clay types, electrokinetics/electrochemical is more effective in silty clay of moderate plasticity (e.g. kaolinite and illite) than in high plastic clays containing swelling clay minerals (e.g. smectites) (Lockhart, 1983).

The importance of soil/mineral type in determining the effectiveness of electrokinetic process could very well be understood by the fact that modification and stabilization process in general among others depends on the nature of surface charge of the clay

minerals which will affect the cation exchange capacity and ion migration. This could well be understood by referring to discussion by Mohamed and Antia (1998). They discussed that they are two major types of surface charged minerals, namely the constant surface charge (fixed charge) and the constant surface potential clay minerals (variable charge). Each has different adsorbtion properties. Imperfection of the lattice structure, such as substitution of aluminium for silicon in a silicate structure or substitution of trivalent aluminium for divalent magnesium in the brucite layer, may lead to an excess of negative charge or positive charge, respectively, at the clay particle surface. Since the imbalance of charge is due to the defect of the crystal and is not influenced by an external factor, the mineral has a fixed charge. Fixed charge minerals include illite, montmorillonite, and chlorite. When the surface charge is generated by the adsorption of ions unto the surface, the net charge is dependant on the ambient pH. Such a mineral is often called a pH-dependant charge or variable charge mineral. Variable charge minerals include kaolinite and hollysite. Since kaolinite shows little isomorphous substitution, more attention should be paid to the broken bonds at the edge of the clay minerals. The broken bonds attract hydrogen or hydroxyl ions from the pore water depending on the pH of the pore water. At a pH below the zero point of charge (pH 4.2), most of the sites on kaolinite become positively charges by attracting extra hydrogen ions. Consequently, the repulsion forces between the kaolinite and the positively charged metal ions in solution are increased. This, in turn, will contribute to an increase in ion migration, and reverse osmosis, that is the direction of water flow is reversed due to positive charges on kaolinite surface. Because ion migration is an important aspect in electrokinetic/electrochemical stabilization and also in electrokinetic remediation of contaminated soil many researches had conducted researches on the buffering capacity on the buffering capacity of the various clay types/minerals.

Phadungchewit (1990) came out with a curve/plot as shown in Figure 2.21 showing the ability of different type of soils to maintain natural pH value over different ranges of acid input. Four kinds of clay material were compared to a 'blank' entity, representing a pure solution without soil. The characteristic shapes shown for the kaolinite soil solution follow the same pattern of the 'blank' indicating the ability of kaolinite to buffer against

acid input. When the soil system pH falls rapidly upon addition of acid, we can interpret this to mean that the soil system shows good ion migration efficiency especially of metal ions and its ability to remain ionic to the acidic environment during the application of electrokinetic treatment. Hence, kaolinite performs better than montmorillonite, natural Quebec soil, and illitic soil as shown in Figure 2.21 as far as ion migration is concerned.

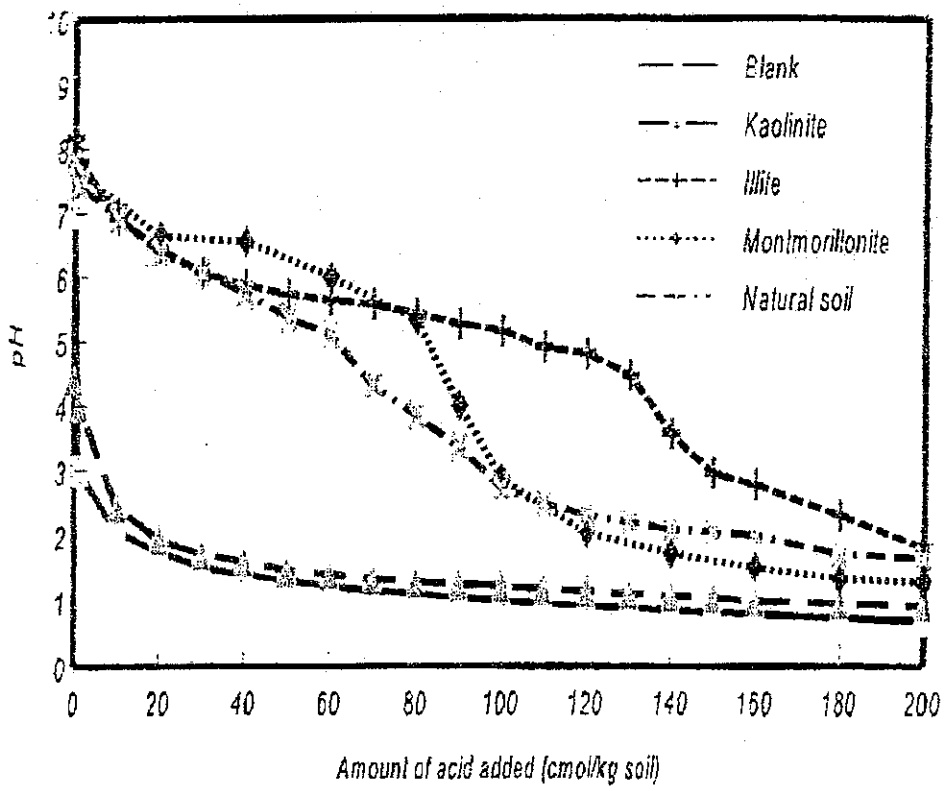


Figure 2.21 pH-acid titration curves for some clay soils and a blank solution (after Phadungchewit, 1990)

This is however probably not preferred in the case of stabilizing effect because in many cases precipitation of ions are required to enhance soil stabilization. In the depolarization technique for example, kaolinite soil would least be affected, hence stabilization might not be as expected due to kaolinite's ability to remain acidic. On the contrary, the buffering capacity of kaolinite against acid input will be beneficial for electroosmotic treatment especially for dewatering purposes. This is because the acid front formed at the anode advances towards the cathode by different transport mechanisms including ion migration and pore fluid advection. Unless the transport of this acid front is retarded by

the buffering capacity of the soil, the chemistry across the specimen will be dominated by the transport of the hydrogen ions. The cation exchange capacity of the soil, the availablility of organic species and salts (such as $CaCO_3$) that react with acid would affect the buffering capacity of the soil. This is where kaolinite clay is good in electroosmotic/dewatering process since kaolinite clay has a much lower buffering capacity compared with other clay such as montmorillonite or illite, due both to its lower cation exchange capacity and the naturally acidic nature of this clay.

As mentioned previously, Ozkan et al. (1999) conducted an experiment to stabilize kaolinite soils by injecting aluminium ions at the anode and phosphoric ions at the cathode to stabilize kaolinite soil. After 15 days of treatment, an average shear strength increase of 500%-600% was obtained in the region of the cathode. Esrig and Gemeinhardt (1967) applied electrochemical stabilization to induced calcium ions to stabilize illitic clay and observed a 100% increase in strength at the end of experiments. Gray (1970) injected aluminium ions into mixes of silica flour with illitic soil and montmorillonite soil. The results show that the strength increased up to 420% for illitic soil and 270% for montmorillonite soil. Gray argued that ion exchanges and mineralization are the major stabilization mechanism for illictic soils and montmorillonite soil respectively. All these experiment results indicate that electrochemical stabilization is possible on any clay/mineral type. However, the efficiency of the treatment is dependant mainly upon what type of chemical or combination of chemicals used in the treatment and also upon the grain size of the soil itself. Regarding to the grain size, most previous studies and application of electrical stabilization of soils have been made of clayey soils. There were in fact very few studies or treatment done on coarser grain material such as silty sand or sandy material. The reason for the emphasis on clays is that much of the stabilization is accomplished by the changes in electrical change on the clay particles by base exchange (for example, Al^{3+} for Na^{+}). This phenomenan implies that if no clay were present, little stabilization and strengthening would occur.

However, Bally and Antonescu (1961) achieved a successful field application on strengthening mine tunnel using electrochemical method on fine silty sand using silicate and calcium chloride solution. Adamson et al. (1967) conducted experiments on fourteen

samples of illitic soil and rock flour found in California and they were treated electrochemically in the laboratoty using various stabilizing chemicals. Among the stabilizing chemicals used were calcium chloride and aluminium acetate. At the end of the experiments he concluded that electrochemical treatment may reduce shrinkage in the case of clayey soil. On the other hand, in the case of 'rock flour', containing very small amount of clay minerals, the reduction in shrinkage may be insignificant. In the latter case, one should attempt to cement the soil through formation of new minerals.

The Russian scientist, Tolstopyatov, 1940 (cited from Adamson et al., 1965) investigated the possibility of electrochemical induration on quartz sand in the laboratory. Induration of quartz sand was possible in the presence of electrolytes and as a result of formation of $Al(OH)_3$ cement. Tolstopyatov observed three distinct zones upon electrical treatment;

1. anodic zone – indurated by aluminium compounds
2. cathiodic zone – indurated as a result of accumulation of calcium hydroxide and cementation with $CaCO_3$ and $MgCO_3$
3. intermediate zone – not indurated and usually susceptible to peptization.

The anodic zone was characterized by the presence of adsorbed and free trivalent cations (Fe^{3+} and especially, Al^{3+}); cathodic zone, by bivalent cations (Ca^{2+} and Mg^{2+}); and intermediate zone, by univalent ions (H^+, Na^+). Coagulation (by Al^{3+} ions at anode, and by Ca^{2+} ions at cathode) which occurs during electrochemical treatment was accompanied by formation of strong microstructure. In the presence of sufficient moisture content, the degree of intergranular cohesion increased as a result of coagulation (Adamson et al., 1965).

Adamson et al., (1967) undertook study to investigate the questions of how much clay is required to be present in a soil before substantial strengthening may be accomplished in electrochemical stabilization. He conducted four series of test by adding low percentage of different types of clays in sandy soil.

In the first sample, the sandy soil was combined with 1.5% by weight of montmorillonite clay. In the second sample, the sandy clay was mixed with 2.5% by weight of kaolinite clay. The third sample, the sandy soil was combined with 2.5% by weight of illite clay and in the fourth test sample, the sandy soil was mixed with a 3.5% by weight composite

sample containing equal amounts of montmorillonite, kaolinite and illite clays. In all the four samples saturated calcium chloride was introduced at one end and then after it had migrated through the whole sample, the polarity was reversed and saturated aluminium sulfate solution was introduced at the other end.

The results indicate increase of cohesion of the order of 100-200 lb/sq.ft and X-ray analysis of treated soils indicate that sheet structures of clays are reduced and silicates destroyed upon treatment. Newly formed minerals were found after treatment which includes gibbsite, limonite, calcite, hydrohematite, hydrogoetite (hydrolepidocrocite), hisingerite, allophone, allophanoid, gypsum, hematite, magnetite, nontronite, trona, and natron ($Na_2CO_3.10H_2O$). He also concluded that the results obtained indicate that there is a possibility of strengthening sandy soils containing small amounts of clay. In addition, reversal polarity at intervals during treatment (for example, every 6 hours) may aid in the strengthening of cementation bonds.

In a much recent research, Fujihira et al. (2000) conducted laboratory investigation on sand using sodium silicate and calcium chloride and found that the strength improvement was probably due to the temperature variation in the soil when subjected to electrical current in the electrochemical process. In providing some previous studies, Table 2.6 is given showing the various experimental and field works conducted in the past and recent years.

Table 2.6 Various reported research and case studies relating to electrochemical stabilization (after Barker et al. 2004)

Reference	Application	Soil	Stabilizer	Comments
Bally and Antonescu (1961)	Mine tunnel strengthening	Fine silty sands	Silicate and calcium chloride solutions	Successful application
Dearstyne & Newman (1963)	Seattle-Tacoma International Airport runway	Clay	Dihydrogenated tallow dimethyl ammonium chloride	Successful application
Esrig & Gemeinhardt (1967)	Laboratory investigation	Illite	Calcium chloride	Calcium ion found to be optimum for illite stabilization
Caron (1968)	Reservoir construction, Tunis	Very soft clay	Ammonium chloride	Increased shear strength
Caron(1971), Peinaud (1977)	Foundation for bridge abutment	Soft to stiff clay	Sodium silicate	Major implementation problems encountered
Yamanouchi and Matsuda (1975)	Laboratory investigation	Liquifiable sand	Silicate solutions, bentonite, aluminium hydroxide	Successful application
O'Bannon et al. (1976)	Highway subgrade, Arizona	Low-plasticity clay	Potassium chloride	Reduction in the degree of swell and swell pressure
Oncescu and Ballie (1977)	Foundation strengthening	Loess	Sodium silicate	Successful application
Anon (1998)	Laboratory investigation	Kaolinite	Aluminium and phosphate ions	Larger increase in shear strength for phosphoric acid than aluminium sulphate
Ozkan et al. (1999)	Laboratory investigation	Kaolinite	Aluminium and phosphate ions	Successful application
Fujihira et al. (2000)	Laboratory investigation	Sand	Sodium silicate and calcium chloride	Temp. variation in ground under electric loading has an influence on strength

iii. type of electrode material and design

Materials used for electrodes influence the performance of the electroosmotic or electrochemical process. Performance here includes the efficiency of the treatment process and also the corrosion and lifespan of the electrodes itself. For dewatering/electroosmotic purpose, excluding expensive materials such as silver and platinum, iron and carbon are more effective than aluminium, lead and carbon black in field applications as observed in experiments (Sprute and Kelsh, 1980; Lockhart, 1983). Iron or steel electrodes have the advantage of low cost whereas copper or brass electrodes are more efficient in current reduction. The design of electrodes includes its geometry, perforation and insulation (if appropriate), and should minimize electric losses which reduce efficiency or even stop the electrokinetic/electrochemical process completely. Therefore, in most applications for electroosmotic treatment, the anodes and cathodes were usually made from reinforcing steel bars, steel pipes, steel tubes or meshes. A layer of sand filter is placed around the cathode to prevent clogging of the cathode. Pumping by means of eductor well is normally required to expel water at the cathode. If copper is used as the anode, copper oxide is formed at the anode with little or no liberation of oxygen. If an inert material is used, such as platinum, oxygen will be liberated at the anode.

The types of electrodes as given above are valid for electroosmotic treatment on soil. When using electrochemical method of treatment, different electrodes might be preferred in combination with specific electrolytes to assist in producing certain reactions, ions or compounds causing modification and stabilization effects in the soil.

For example, in their investigation, Gray and Schlocker (1969) used aluminium anodes to electrochemically treat different type of clays. Aluminium anodes were singled out for the experimental study for two main reasons.

a. Aluminium anodes are often used in engineering practice for electroosmotic dewatering

b. Aluminium can combine with hydroxide ions to form various hydroxyl-aluminium compounds in soils. These compounds have interesting properties in the sense that they can interlayer with certain clay materials or precipitate externally in the pore space as amorphous or crystalline hydroxides and thus modifying the mineralogy, composition and presumably the physical properties of the soil.

In the same experiment they also observed that the use of aluminium anodes effectively buffered the anolyte at a pH of 3.8 whereby by using graphite anodes for example, the pH will drop to as low as 1.2 in the anolyte. There was also an increase in resistance across the soil sample with time which was caused in some instance by the behavior of the aluminium anodes. This behavior comfirms the finding by Jenny, 1940 (cited from Gray and Schlocker, 1969) that typically when aluminium is used as an anode, it tends to develop large resistance to current. Adamson et al. (1965) found that solid aluminium electrodes should be used as anodes whenever possible; aluminium anodes provide Al^{3+} ions for base exchange and cementation leading to a irreversible process. Experiments conducted also showed that cracking in expansive soils can be considerably reduced if aluminium is substituted for other cations in the clay structure and could be achived by using aluminium anodes. These positively charged ions apparently produce a stronger bond between the clay particles and unify the clay mass. As far as the arrangement of the electrodes is concerned, Eggestad (1984) reported that the efficiency of the electroosmotic treatment was enhanced by giving two neighboring rows the same polarity. This enhancement could also possibly be applicable in electrochemical treatment. Mitchell (1981) has reported that a hexagonal arrangement of anodes around a central cathode is more efficient than linear rows or square pattern. He also suggested that in field applications, increasing the number of anodes relative to the cathodes is generally beneficial for two reasons;

i. If well points are used as cathodes, and reinforcing bars or aluminium rods are used as anodes, this will reduce the overall cost of electrodes.

ii. As anodes decompose, they participate in the electrochemical hardening of the soil.

2.3.4 Changes of parameters/variables during electrochemical process

There are several different chemical, electrical and electrochemical processes that become active within the soil-liquid medium when a soil is subjected to electrochemical processing. These processes change the system chemistry and collectively affect the soil micro-structure, consequently modifying many soil properties (Jayasekara and Hall 2007). These processes in the course of the treatment results in the changes of some of the parameters/variables normally associated with electrochemical modification and stabilization which as stated above, eventually modifies the soil properties. The mechanism of changes in these parameters and factors affecting them are in nature more complex than what is found in the traditional chemical stabilization and merely electroosmotic treatment, and hence, need somewhat detail elaborations. Those changes of parameters that are related to electrochemical process during the course of treatment are;

i. pH
ii. atterberg limit
iii. conductivity/resistivity
iv. current
v. voltage
vi. zeta potential

2.3.4.1 Changes in pH

The role of pH or changes in pH in both electroosmotic and especially in electrochemical treatment is perhaps the governing factor in the effectiveness of modification and stabilization process in soils. The mechanism that leads to the changes of pH throughout the soil is given as follows (Acar and Alshawabkeh 1997):

The alkaline medium developed at the cathode due to the production of OH^- will initially advance towards the anode by diffusion and ionic migration; however, the counterflow due to electroosmosis will retard this back-diffusion and migration. The advance of this front towards the anode will be much slower than the advance of the acid front towards the cathode because of the counteracting electroosmotic flow and also because the ionic

mobility of H^+ is about 1.76 times that of OH^-. As a consequence, the acid front dominates the chemistry across the specimen. Figure 2.22 displays development of the acid/base profile across a 10 cm length cylindrical Georgia kaolinite specimen processed under one-dimensional conditions at a current density of 12.5 $\mu A/cm^2$ (Acar et al. 1990).

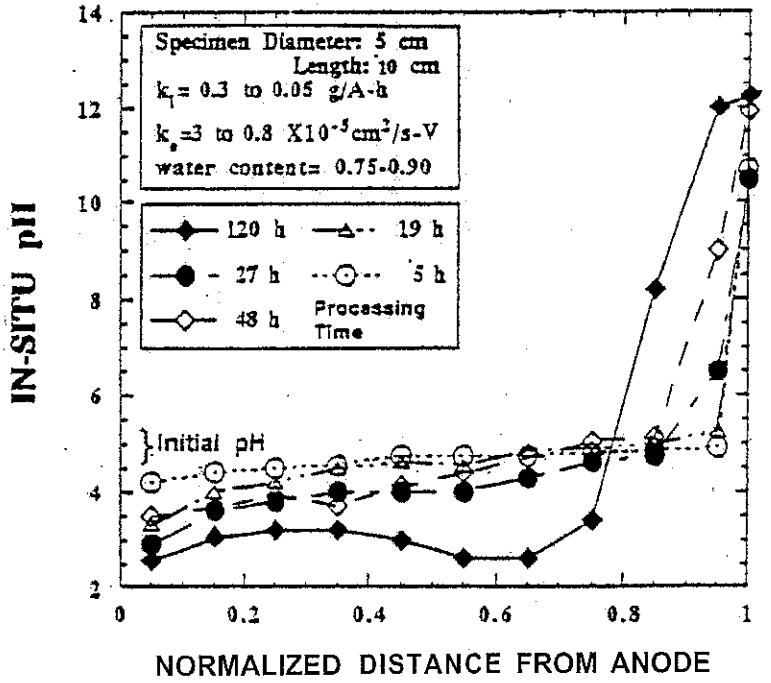


Figure 2.22 Acid/Base distribution across specimen of slurry consolidated Georgia Kaolinite processed under an electric current of 12.5 $\mu A/cm^2$ (after Acar et al. 1990)

The changes in pH in the soil-water system will result in the improvement of soil characteristics and strengthening. These effects are made possible through three mechanisms;

i. cations replacement resulting in flocculation and coagulation.

ii. precipitation of species in the pore fluid.

iii. cementation/mineralization.

The three mechanisms above were mentioned in the previous section 2.3.1 but are elaborated further in relation to pH in the following paragraphs.

Cation replacement in relation to pH - Electrolysis of the pore water at the electrodes causes hydrogen (H^+) and hydroxide (OH^-) ions to be released from the anode to cathode respectively where these ions are drawn towards the opposing electrodes. There are therefore differentials in pH level across the soil mass. These pH variations in turn change the surface charge on clay minerals, and thus the cation exchange capacity and the solubility of elements within the soil structure. The results of these cations exchange causes flocculation and results in changes in the soils workability, permeability, Atterberg limit, plasticity and swell properties.

Ozkan et al. (1998), confirmed the fact that acidic soil condition cause ionization of kaolinite, dissolve basic precipitates, desorb surface cation species into the pore fluid, and lead to a flocculated soil structure.

Thomas and Lentz (1990) agreed to the fact that most method of soil stabilization involves creating a flocculated soil structure and this can be readily achieved by replacing monovalent cations on the clay surface with multivalent cations. A reduction in soil pH is an effective method of replacing monovalent cations. As soil pH decreases, aluminium ions in the clay structure replace hydrogen and other ions on the clay surface, resulting in multivalent ions present on the clay surfaces and a more flocculated soil structure.

The decrease in pH value in the soil depends on the amount of acid generated at the anode (Acar et al., 1990, 1993) and the buffering capacity of clay. Yong et al., 1990 (cited from Acar et al., 1997) investigated the buffering capacity of various types of clays and demonstrated that the cations exchange capacity and the organic content highly influenced the soil pH. Futhermore, the study showed that kaolinite has low buffering capacity compared with different type of clayey soils.

In kaolinite clay soils, at time the value of Plasticity Index (PI) will increase after treatment. In a test conducted by Jayasekara and Hall (2007), using saturated lime on heavy clay, the test showed that there was a significant change in the Atterberg limits. The PL and LL increase with a reduction in PI. In general, the decrease in PI value indicates the effects of agglomeration/flocculation reactions and the subsequent pozzolanic reactions that lead to decrease in soil plasticity, which is a major benefit in chemical stabilization.

Adamson et al. (1967) evaluated the effect of $CaCl_2$ solution on clayed silt which causes plastic limit rose from 21.2% to 23.9% whereas the liquid limit increase from 27.9% to 30.2% and the PI was practically unchanged. Ozkan et al. (1998) conducted several tests on chemical stabilization of kaolinite. In an experiment using phosphoric acid injected through both anode and cathode, the liquid limit and plastic limit values of the soil increased after the experiment. The liquid limit varies in the soil mass from 52% at the anode to 80% at the cathode, while the plasticity index increase, on average, from 26% - 35%. This increase in Atterberg limit is a good indicator that pozzolanic reactions are taking place.

It is important to note here that in general the desired changes in Atterberg limits would be the reduction in the plasticity or the Plastic Index (PI) which is normally the result of increase in plastic limit and reduction in liquid limit. However in general, one could say that any changes in Atterberg limits of a particular soil should alter the strength of the remolded soil at a particular moisture content. The change in Atterberg limit indicates that ion exchange had taken place and one would expect that increasing the liquid limit of soil at a particular mixture content would increase its strength, and as a consequence, decrease its compressibility under a particular increment of stress that is causing the soil to behave as though it were consolidated (Esrig, 1967). Lo and Ho (1990) conducted an experiment to improve the soil properties of soft clay reported that the increase in liquid limit may be due to the increase of salt content of the soil after treatment.

Bergado (2003) states that the liquid limit is influenced by such factors as exchangeable ion, salt concentration and pH of the clay and confirmed on the increase of salt concentration after electrokinetic treatment. The experimental results by Abierra et al., (1999) showed that for the low swelling but sensitive mectite Ariake clay in Japan where particle arrangement is the dominant force, the Atterberg limits increase after electrokinetic treatment are due to the increase in salt concentration or salinity in which the benefit of increasing salinity results in the improvement of the soil structure in the form of better cementation bonding of soil particles and consequently increases the shear strength and reduces the sensitivity of the clays. Lo and Ho (1990) confirmed on the fact that increase in plasticity, carbonate content and salinity results in bonding of soil

particles and the reduction in the thickness of the double layer and as a result, the soil becomes less sensitive.

Precipitation in relation to pH - Hamed et al. (1991) denotes that the production of H^+ ions at the anode creates an acid front which moves from the anode to the cathode by

i. migration due to electrical gradient
ii. diffusion due to concentration gradient and
iii. convection of the pore fluid due to the prevailing electroosmotic flow and the hydraulic gradient

As the acid front moves from the anode to cathode, the H^+ ions exchange with the adsorbed cations in the diffuse ion layer around clay particles. This cation exchange process releases the heavy metals into the pore fluid, which are then advanced toward the cathode by advection and diffusion. In addition, low pH solution dissolves heavy metal precipitates (e.g. carbonates and oxides), and increases heavy metal concentration in the pore fluid. An increase in H^+ concentration associated with a decrease in pH results in the desorptions of cations by an amount controlled by the soil type (Maguire et al. 1983, and Yong et al. 1990). At the cathode, a base front is developed and this base front generated by electrolysis at the cathode will cause precipitation of most heavy metals and actinides (Acar and Alshawabkeh, 1997). The amount of precipitate differs from one species to another and it is dependant on the soil and pore fluid pH. The advance of acid front generated at the anode is also expected to cause dissolution of clay minerals. The hydroxides ions formed at the cathode migrate toward the anode. These hydroxide ions tend to form metal hydroxide precipitates when they encounter the metal ions which are being transported to the cathode by the electroosmotic flow. It should be noted that at a much higher pH values, the solubility of metals increases once again due to the formation of soluble complexes which can have neutral, positive or negative charges (Mohamed, 2000) as shown in Figure 2.23.

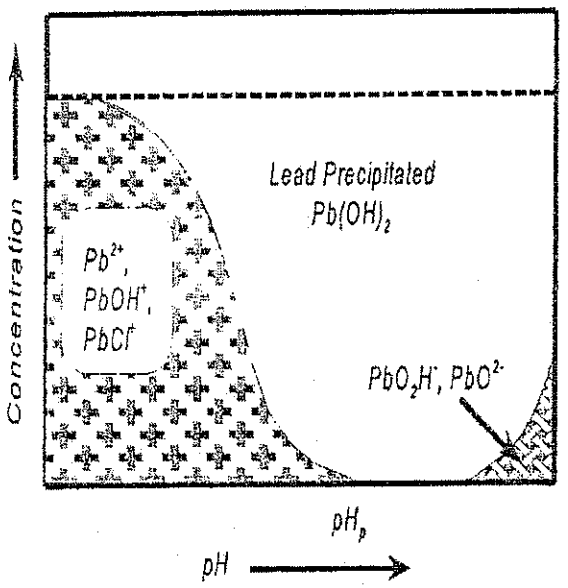


Figure 2.23 Formation of lead precipitates and ions as a function of pH (after Mohamed and Anita, 1998)

Cementation/mineralization in relation to pH - In the case of stabilization process through cementation/mineralization, alteration of the soil pH results in changes in the solubility of the clay minerals present. For instance, the solubility of aluminium oxide (a mineral commonly found in clay) increases dramatically when the soil pH is below 3.5 or above 10.0 (Loughnan, 1969). Barker (2004) reported that the dissolution of alumina occurs in only small quantities at a pH less than 7, starts to increase significantly at a pH>8, and reaches a maximum at pH>10. Similarly, dissolution of silica is negligible at pH<8 and reaches a maximum at pH>10. Thus mineral dissolution will occur where the pH has altered sufficiently through a combination of electrolysis, corrosion and migration. Once dissolved, these minerals-essentially alumina (Al_2O_3) and silica (SiO_4) may react with for example calcium ions, which may be purposely introduced into the soil system, and are present in the pore water, as a result of ion migration from the chemical source. The reaction products are armorphous calcium aluminate hydrate and calcium silicate hydrate gels, which thereafter crystallize with time to form a strong cementitious material.

Jayasekara (2007) conducted an experiment to look into several aspects of changes in soil properties using electrochemical treatments. The soil samples were supplied with a continuous flow either distilled water or saturated lime solution (CaO dissolved in distilled water) via the hollow core anode from external reservoirs. The soil samples were subjected to a direct current (DC) with a constant voltage gradient of 0.5V/cm for a period of 14 days. After the electrochemical processing period (14 days), the soil between the electrodes was divided in to five sections defined by their average normalised distance (0.1, 0.3, 0.5, 0.7, 0.9) from the anode, and were tested for their physical and chemical properties.

The results of pH variation across the tank with distilled water and lime enhancement in presented in Figure 2.24.

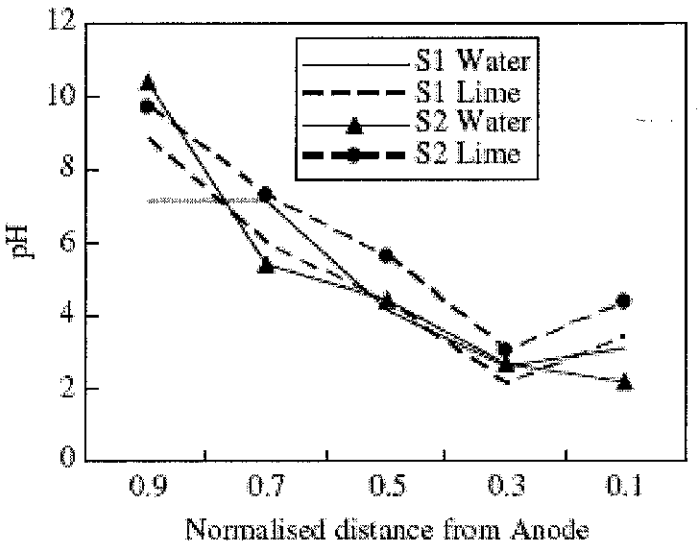


Figure 2.24 Variation of pH across the tank with lime and distilled water enhancement (after Jayasekara and Hall, 2007)

It is observed that a clear pH gradient is developed across the tank creating an acid front at the anode and a base front from the cathode with pH ranging from 3-10. With the introduction of lime especially for soil 2 (S2), there was a decrease in the acidity at the anode due to neutralizing effects of the highly alkaline lime solution on the developing acid front. The results from the test with distilled water comply with the general rule that the following reaction will occur at both the electrodes:

At the anode $2H_2O - 4e^- \rightarrow O_2 + 4H^+$

At the cathode $2H_2O - 2e^- \rightarrow 2H_2 + 2OH^-$

The reactions resulted in the formation of hydrogen ions and oxygen at the anode and hydroxide ions and hydrogen at the cathode. As the ionic mobility of hydrogen ion is approximately 1.8 times faster than hydroxide ions and the electroosmotic flow is toward the cathode, almost the entire soil mass was subjected to acidic condition (pH<7) developed from the anode onwards. The corresponding results on the variations on current value, electrical conductivity, compressive strength and water content are given in Figures 2.25, 2.26, 2.27 and 2.28 respectively. All figures shown are meant to indicate the possible changes of the above mentioned factors in relation with the variations of pH. Whether the factors are inter-dependant with changes in pH will not be discussed in detail here as further discussions in variations of current and conductivity will be elaborated later.

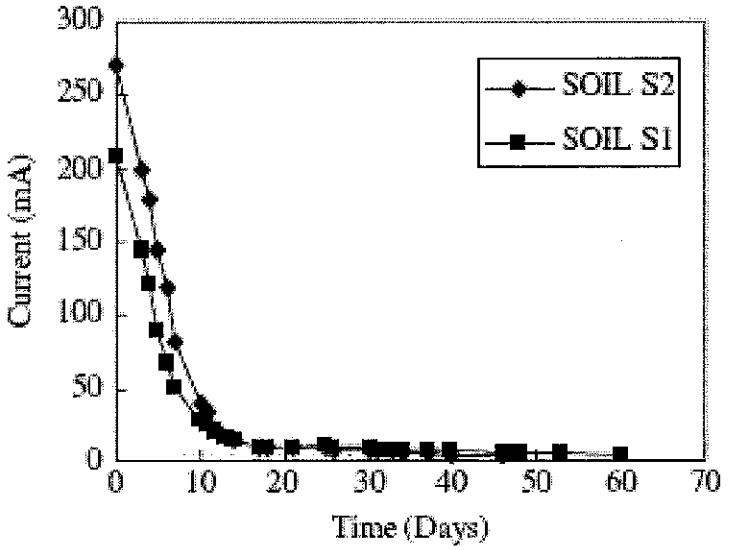


Figure 2.25 Variation of current flow across the tank with time (after Jayasekara and Hall, 2007)

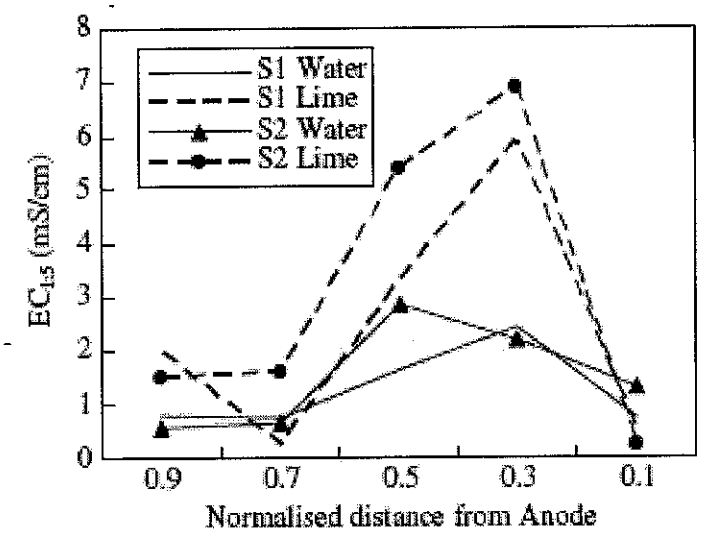


Figure 2.26 Variation of electrical conductivity across the tank with lime and distilled water enhancement (after Jayasekara and Hall, 2007)

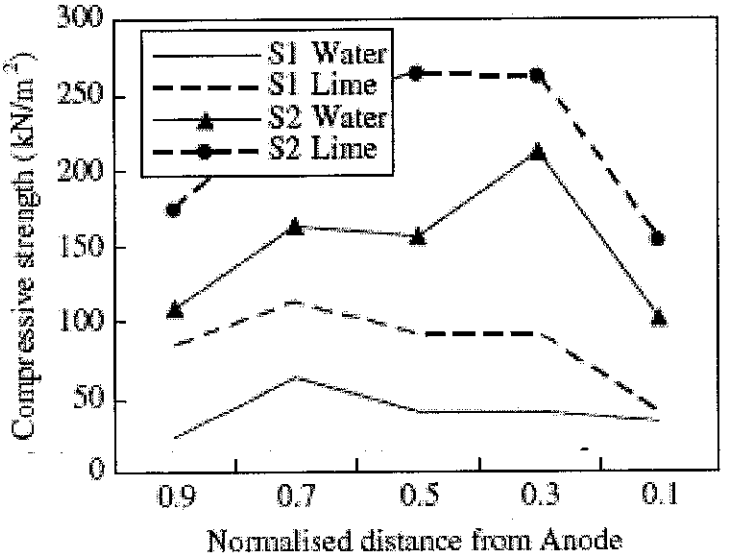


Figure 2.27 Variation of compressive strength with lime and distilled water enhancement (after Jayasekara and Hall, 2007)

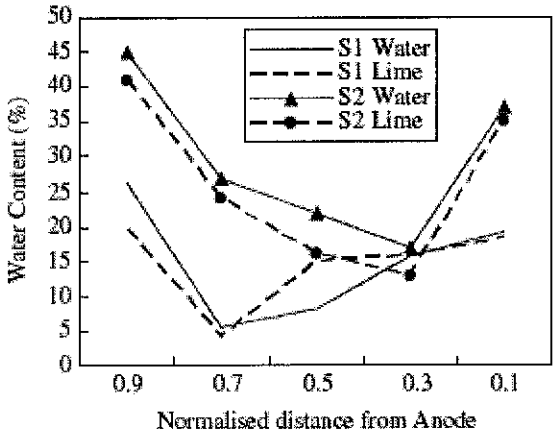


Figure 2.28 Variation of water contents of soil S1 and S2 with lime and distilled water enhancement (after Jayasekara and Hall, 2007)

Alshawabkeh and Sheahan (2002) evaluated how the injection of phosphoric acid at the cathode can cause phosphate ions to migrate into Boston Blue Clay under 1V/cm DC fields.

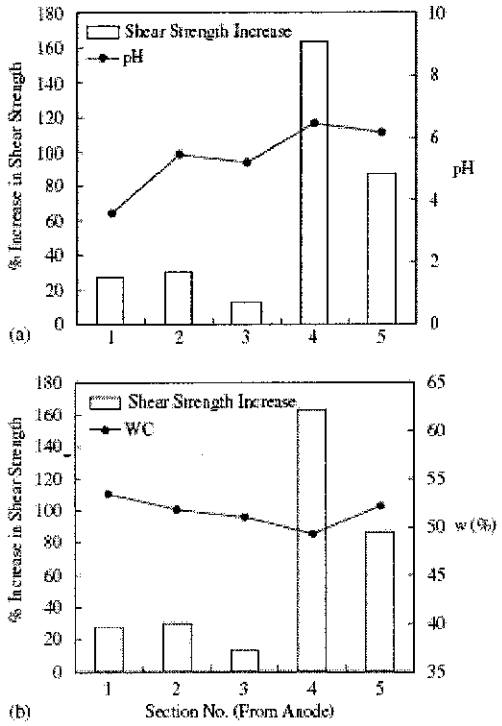


Figure 2.29 Results through the electrochemical specimen after two weeks of phosphate injection: (a) percent increase in undrained shear strength and pH; (b) percent increase in shear strength and water content (after Alshawabkeh and Sheahan, 2003)

By injecting phosphoric acid at the cathode maintaining the catholyte pH around 5, the soil specimen were processed in an electrochemical treatment set up under constant conditions and monitored for two weeks. From Figure 2.29, final pH profile showed that the soil's pH ranged between 4 and 7. The results also show an increase in the shear strength across the specimen. Sections close to the cathode (Section 4 and 5 in Figure 2.29) showed the highest increase, 90% to160% of the initial shear strength, while the smallest increase (10-20%) was at the middle section.

The increase in shear strength in section 4 and 5 was due to higher pH levels causing precipitation of phosphate in the soil, hence proving the importance of pH value in the strengthening process of the soil. An interesting fact to note here is that Alshawabkeh found that the final water content across the specimen was greater than the original 49% which confirms that the increase in strength was not related to soil consolidation which is a consequence of electroosmotic process.

Baker et al. (2004) did a field test on glacial clay using mild steel tubes as electrodes. The calcium chloride ($CaCl_2$) solution was applied through the anode and sodium silicate (Na_2SiO_3) solution applied through the cathode. Potential difference was initially set at 8V for 0-4 days and was thereafter raised to 20V for 4-12 days and 50V for 12-27days. Results show that the pH was found to increase in the region close to the cathode and decrease in the region close to the anode, owing to the electrolysis of pore water and oxidation, reduction reactions. However, looking at the pH value of 8.5 at the cathode and 7.4 close to the anode, the variation of pH value throughout the soil was just about 1.1 with the average initial pH of 7.5. Interesting enough, even though the increase in pH was small, formation of calcium silicate hydrate was detected after 27 days of treatment.

Thomas and Lentz (1990) conducted a test on a soil mixture of sand, silt and clay in which phosphoric acid was injected through the cathode. The soil was mixed at a ratio of 30% fine sand, 30% silt, 30% kaolinite and 10% montmorillonite. After 30 days soil sample taken at the anode, center and at cathode flocculated with the sample near the anode experienced a quicker flocculation process than the other two. Final pH values were 6.1 near the cathode, 6.4 at the center and the 3.2 near the anode. Relatively minor changes occurred in the liquid limit (LL) and plastic limit (PL) with little or no change in

plasticity index (PI). In contrast, the shringkage limit (SL) increase near the anode from the initial value of 12 to 18. Strength increase was noticed at the anode with moisture content similar to those at initial condition. This strength increase near the anode could be attributed to changes in the clay structure accompanying a reduction in pH. As the soil pH decreases, aluminium ions from the clay structure replace free hydrogen on the clay surface, resulting in a flocculated, more stable structure (Coleman, 1961). In addition, low pH value causes an increase in edge-to-face contacts in kaolinite (van Olphen, 1963). The movement of aluminium ions from the clay structure to the surface reduces the amount of adsorbed water in the clay and reduces the LL. The more flocculated structure related to the decrease in pH caused an increase in both the PL and SL. In other words, specifically the increase in SL is cause by a change in soil structure from dispersed to flocculated. By increasing the SL, one has effectively reduced the shrink-swell potential of a soil. The change will only occur if electroosmosis/electrochemical is continued long enough to decrease the pH enough to cause aluminium ions to move out of the clay lattice. In addition, the shrink-swell potential of a soil is reduced by the inability of the clay layers to swell apart when the exchangeable cations are aluminium.

2.3.4.2 Electrical conductivity, current change, resistivity and voltage

It is evident from most tests that in general, changes in the electrical conductivity is one of the most important parameter in ensuring effectiveness of the electrochemical process. The conductivity of a solution is governed by the movement of ions within a solution. The factors affecting solution conductivity include (Barker et al., 2003);

i. nature of concentration of solutes.
ii. quantity of ions within the solution.
iii. change of each ion within solution.
iv. freedom of ionic movement within solution.
v. solution temperature.

With respect to the conductivity of the soil undergoing treatment, the specific factors affecting conductivity include the following;

i. the solubility of the minerals present, which is a function of pH

ii. migration of ions into and out of the soil. The applied current would cause anions and cations within the pore fluid to migrate towards the anode and cathode respectively. Ions are also introduced through the addition of chemical solution through the electrodes and corrosion of the anode.

iii. precipitation of compounds as ions mix within the pore fluid. As the species of ions alter within the pore fluid, components are formed that may be more sensitive to changes in pH over the ranges observed, thus resulting in precipitation.

The electrical conductivity of soil also depends on the surface conductivity of the mineral particles and the concentration of hydrogen, hydroxyl, and other ions in the pore fluid (Rhodes et al., 1989). The electrical conductivity of the ground increases with the concentration of salts in the ground water; and increase more markedly with growing concentrations in low-concentration solutions than in high concentration solution, Rel'tov et al., 1955; Ziangirov, 1956 (cited from Adamson, 1965).

Referring back to the experiment conducted by Jayasekara (2007) using CaO injected through the anode, in general the electrical conductivity (EC) across the soil specimen gradually reduced when moving from anode towards the cathode where the lowest electrical conductivity zone occurred close to the cathode at a normalized distance of 0.7 from the anode. Large electrical conductivity values were observed towards the anode and they were due to the generation of H^+ ions that are highly conductive (mobile) in solution. The gradual migration of these H^+ ions from anode towards cathode increased the electrical conductiviy values proportionately across the inter electrode space. A high conductivity values were recorded in the middle of the specimen as a result of electromigration of both the hydrogen ions and calcium ions that were produced at the anode and the somewhat lower electrical conductivity values observed at the cathode was due to the neutralization of alkali front, which is associated with calcium hydroxide [$Ca(OH)_2$] precipitate under the alkaline condition at the cathode. At the anode, the mild steel electrodes oxidized and produced Fe^{3+}. These ions are also susceptible to migration from the anode towards the cathode and can interact with clay minerals. Hence, these ions could also contribute to the electrical conductivity of the soil at different region. Therefore, the electrical conductivity of the soil at any given location along the soil

across the section depends on the amount and conductivity of ions present. Since H^+ ions are considerably more mobile in solution compared to other ions, the concentration of H^+ ions contributes greatly to the electrical conductivity of the soil.

Alshawabkeh and Sheahan (2003) conducted an experiment on a clayed soil by injection of phosphate through cathodes and observed that after 24 hrs of treatment, phosphate ions starts migrating into the soil and precipitating with the soil mineral, thus decreasing ionic content of the pore fluid and the electric conductivity of the soil at the cathode. Ahmad et al. (2001) also observed the same trend of reduction of soil conductivity which results in the decreasing of current with time. He presumes that the decrease in electrical conductivity and current were due to precipitation at electrodes, air bubble formations due to electrolysis at the electrodes chambers, etc.

From the preceding paragraph it is clear that electric current varies in time depending upon the changes in the electrical conductivity of the soil. In the same experiment above, Alshawabkeh (2003) observed that the increase of current in the first 24 hrs was due to an increase in the electric conductivity of the system between the electrodes. This was due to the effect of electrolysis on the anolyte and catholyte. Applying the current and addition of acid at the cathode increased the ionic strength of the electrolytes and increased electric conductivity of the system, thus increasing the current. After 24 hrs as mentioned above, due to precipitation, ionic content reduced and thus electrical conductivity and current were also reduced. Current reduction during electrochemical treatment could also be partly the result of a decrease in the water content in the vicinity of the anode leading to an increase in soil resistivity. Current reduction could also be the result of evaporation of water into the atmosphere.

It has been reported that where a soil is dewatered by electrokinetic process, a dry zone occurs around the anode, and that soil near the anode can become impregnated with iron oxide. Over time, iron oxide fills voids and caused chemical cementation of pore spaces. Iron oxide cementation around the anode cause by 'dredging' or iron from groundwater can become so extensive that the electrokinetic/electroosmotic currents are virtually shut off by barrier formed around the anode.

Kassim et al. (2003) conducted an experiment by injecting $CaCl_2$ and distilled water at anode and cathode respectively; distilled water and phosphoric acid (H_3PO4) at cathode in the other experiment. He noted that the variations of current densities in electrokinetic treatment were due to the dynamic of the electrochemical processes which took place within the system (Figure 2.30). The increased in current density indicated the decrease in resistivity of the systems, and vice versa. Futhermore, the increase and decrease of the current and hence the resistivity could take place in the soil, in the anolyte, in the catholyte, or the combination of those media. In addition, the presence of ions namely H^+ and OH^- ions in the $CaCl_2$-distilled water and distilled water-H_3PO_4 systems, respectively, also contributed to the variation in current densities. Lockhart (1983b) found that added electrolytes might contribute both anions and cations but the direct current might not increase in proportion. This extra current however contributed to the increase in net flow of water

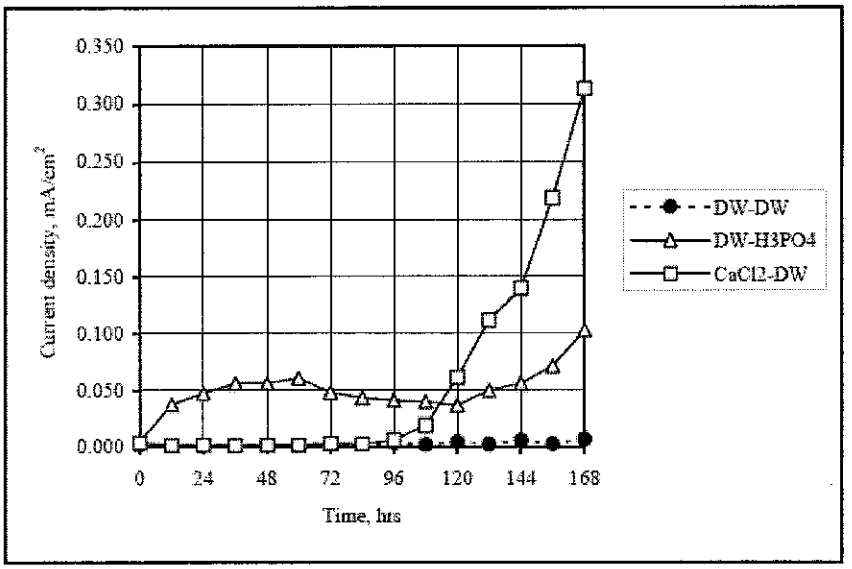


Figure 2.30 Variations of current densities with time (after Kassim et al., 2003)

Naggar (2004) studied the effect of electrokinetic treatment on piles and found that current decrease during treatment was primarily the result of a decrease in its water content at the vicinity of the anode leading to an increase in the soil resistivity, and ultimately corrosion of the anode.

In conclusion, electrical profiles provide an indirect assessment of the chemical changes in the ionic compositions of the pore fluid (West et al., 1999). Wherever there is an increase or reduction of current as a result of corresponding increase or decrease in electrical conductivity, two other related parameters will also be affected and they are the voltage and the resistivity of the system. This is because the voltage gradient and resistivity are related to current density by Ohm's law where;

$$I = \frac{V}{R} \tag{2.34}$$

where I = current

V = voltage

R = resistivity

In fact Alshawabkeh and Sheahan (2003) stated that a critical parameter in evaluating the electrokinetic technology is the energy expenditure across the soil. They noted that, a linear voltage distribution should occur across the treated soil specimen if the electric conductivity is uniform in the soil between the electrodes and this is the case initially at the beginning of the treatment (at time zero). Figures 2.31 and 2.32 show results of voltage distribution along the soil sample and changes of electrical current with time in an experiment conducted using phosphoric acid by Alshawabkeh and Sheahan (2003).

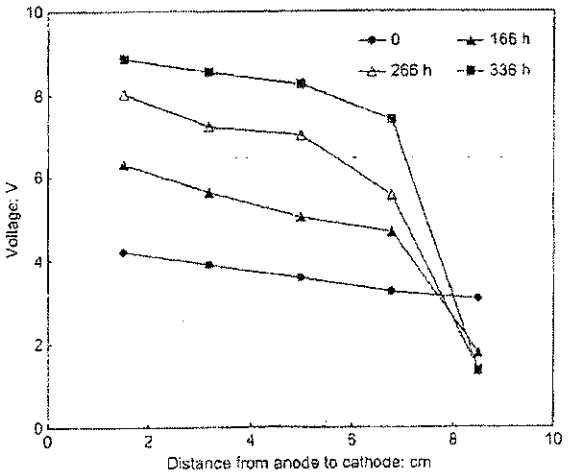


Figure 2.31 Voltage distribution in soil between anode and cathode in treatment with phosphoric acid (after Alshawabkeh and Sheahan, 2003)

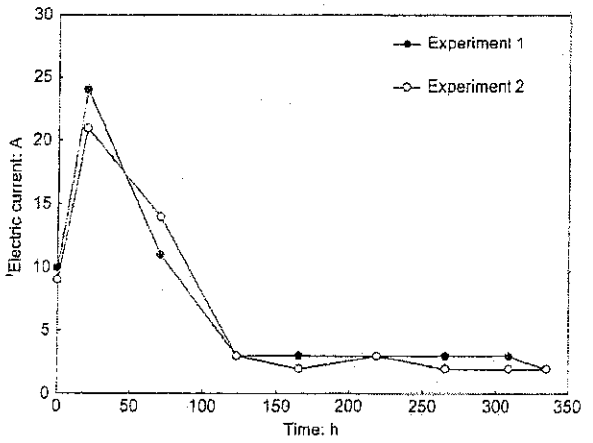


Figure 2.32 Changes of electric current versus time in treatment with phosphoric acid (after Alshawabkeh and Sheahan, 2003)

However, during processing and as phosphate migrates and precipitates near the cathode, a zone of high electrical resistance starts developing nearest to the cathode and extends through the specimen half closest to the cathode. This was probably due to the precipitation and mineralization of phosphate in the soil pores. The anode maintains a relatively conductive environment. The increase in electrical resistance of the specimen results in higher energy expenditure.

In an experiments conducted by Kassim et al. (2003), he observed that the voltage gradients across the soil sample during the electrochemical processing were found to vary with time for all cases (Figure 2.33). The changes in voltage gradient in general were mainly because of the changes in the resistivity of the soil. Resistivity of a soil could be increased due to formation of water by H^+ and OH^- within the soil sample, precipitation of hydroxides, or changes in pH of soil or the combination of these factors (Puppala, 1994). Kassim et al. (2003) also observed that the introduction of phosphate ions in the cathode compartment for the distilled water-H_3PO_4 system resulted in the formation of phosphate compounds which cause resistivity of the soil to increase. As a consequence, the voltage gradient increased to the maximum 3.9V/cm. Nonetheless, the voltage gradient decreased after 120 hours of processing. This might be caused by ionization of certain compounds in the soil as a result of migration of H^+ from the anode toward the cathode.

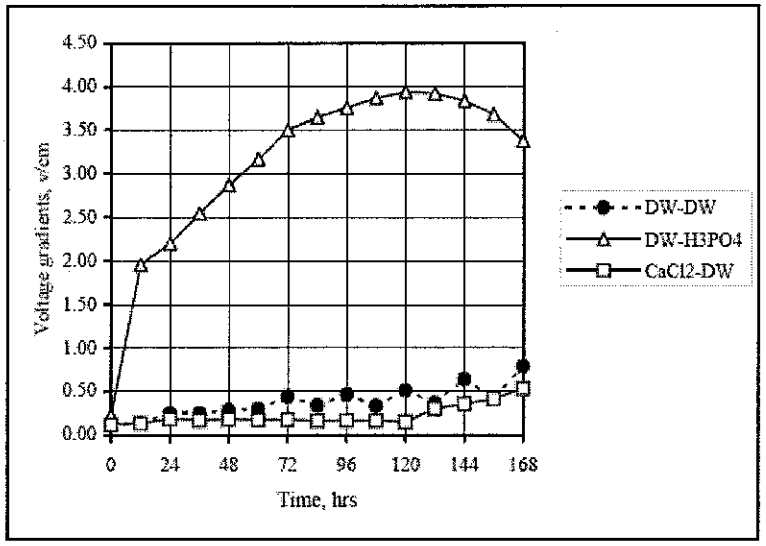


Figure 2.33 Variation of voltage gradient with time (after Kassim et al. 2003)

On the other hand, calcium ions introduced in the anode compartment for the $CaCl_2$-distilled water system did not increase the voltage gradients of the soil significantly. The presence of calcium ions that remained ionic in the pore fluid might be the reason for this phenomenan because calcium ions could not precipitate in acidic environment.

Therefore, it could be understood here that low electric conductivity and low current values near the cathode resulting from an increase in resistance causes a higher voltage drop near the cathode compared to sections near the anode.

The high resistivity zone, demonstrated by a sharp drop in the electrical potential (voltage), not only indicates uniformity of the ionic composition but also identifies the location of the precipitation zone (Page and Page, 2002).

2.3.4.3 Zeta-potential

It is very essential to understand at this point that with regard to electrical treatment to stabilize soils, in many cases electroosmotic transfer of water inevitably accompanies the process. Especially in the beginning of the electrochemical treatment, electroosmosis/dewatering process is somewhat desired in playing an important role in strengthening the soil through consolidation. When chemicals (anions and cations) are

placed in the vicinity of the anode for example, and electroosmotic transport prevails in the soil, again especially at the beginning of the process, cations are transported from the anode to the cathode both by electroosmosis and electromigration. Because the directions of both transport mechanisms are the same (i.e. from anode to cathode), cation transport from cathode to anode is enhanced by the combined effects of both electroosmosis and electromigration. Therefore, under certain conditions (such as presence of appropriate mineral, high water content and low ionic strength of pore fluid) electroosmosis will have a significant role in electrokinetic soil remediation. As explained earlier, the rate of electroosmotic flow is controlled by the coefficient of electroosmotic permeability of the soil (k_e), which is measure of the fluid flow per unit area of the soil per unit electric gradient. The value of k_e is assumed to be a function of the zeta potential of the soil-pore fluid interface, the viscosity of the pore fluid, soil porosity, and soil electrical permittivity. When the soil pores are treated as capillary tubes, the coefficient of electroosmotic permeability is given by;

$$k_e = \frac{\varepsilon\zeta}{\eta} n \qquad (2.35)$$

Where ζ = zeta potential (V)

n = porosity

η = viscosity (FT/L^2)

According to Helmholtz-Smoluchowski's theory, the electroosmotic coefficient of permeability k_e, is dependant mainly on porosity and zeta potential. The value of k_e has been assumed to be constant during the electrokinetic/electrochemical process as long as there is no change in the concentration of ions or pH of the pore fluid. It is hypothesized that the drop in pH of the soil due to electrochemical processing will cause a decrease in the coefficient of electroosmotic permeability associated with the drop in zeta potential; hence, the electroosmotic flow will start to decrease and eventually stop at later stage of the process.

Vane and Zang (1997) investigated the effect of pore fluid properties on electroosmotic permeability. The results displayed that the effect of pH on zeta potential and

electroosmotic flow vary significantly depending upon the mineral type. Lockhart (1983) demonstrated that high electrolyte concentration in the pore fluid caused strong electrolyte polarization which limit electroosmotic flow. Conventionally, electroosmotic flow in clayed soils takes place from anode toward cathode as most particle surfaces are negatively charged as a result of isomorphous substitution and the presence of broken bonds. In order to balance the charge deficit, the mobile ions in the pore fluid have to be positively charged. In most clays, the range of values of zeta potential is between 0 and -50 mV depending upon the chemistry of the soil system (Yeung et al., 1997). At a certain pH value and pore fluid ionic strength, the soil surface charge could drop to zero rendering a zero zeta potential or what is called the iso-electric point (Lorenz, 1969). Negative surface charge of clay particles (negative zeta potential) causes electroosmosis to occur from anode to cathode while positive surface charge causes electroosmosis to occur from cathode to anode (Eykholt, 1992; Eykholt and Daniel, 1994). The electroosmotic flow can virtually be eliminated at the iso-electric point or zero zeta potential. Vane and Zang (1997) confirms the fact that the change in flow direction also indicates that the sign of zeta potential changed with time during the experiments are due to changes in soil pH. In addition, the pH at which polarity reversal of zeta potential takes place depends on the physicochemical properties of the soil and pore fluid (Yeung et al., 1997). According to Gurtu (1977), the sign of charge in most cases can be changed by the addition of extremely small quantities of certain electrolysis in water. Alshawabkeh et al. (2004) reported that acidification of sections near anode causes a decrease in the negative charge, zeta potential and electroosmotic flow. In some cases, a reverse in surface charge occurs causing an electroosmotic flow towards the anode. At the same time, the high pH zone near the anode maintains a higher negative surface charge, zeta potential and electroosmotic flow towards the cathode.

In general one could say that the factors affecting zeta potential are;

i. pH of the soil-water system
ii. conductivity
iii. concentration of the fluid/electrolytes in the soil-water system

2.3.5 Concluding remarks and summary of main objectives of study

After going through the literature review, one could conclude that the electrochemical process in soil treatment; its mechanism, system chemisty, governing factors that controls the whole process, effects etc., are at times very complex. Too many parameters/variables are simultaneously involved in a single electrochemical treatment which causes difficulties in determining which parameter is responsible for a particular effect or outcome during the process of treatment.

Other points which one could also conclude from the literature review are;

i. Most studies in the past were focused on fine grained soil which in many cases have been proven to work successfully whether in laboratory environment or at site.
ii. Concentration of researchs was either in electroosmotic or electrochemical treatment. The author feels that it is important to have some appropriate amount of tests involving both methods in order to make significant comparisons between the two types of treatments.
iii. Experiments to look into the effects of electroosmotic and electrochemical treatments on soil particles passing different sizes of sieves using the same soil type have not been done before.
iv. No specific laboratory experiments simulating slope conditions was done before.
v. Many of the soil types especially kaolinite soil subjected to both methods of treatment were mainly conducted abroad. A dedicated research using local kaolinite soil is vital since soil, although of the same type, will possibly exhibit different soil characteristics and properties.

Therefore, in the effort to address those issues mentioned above, the author has incorporated them as part of this research. The overall main objectives of research however, are again summarized as follows;

i. Investigating the phenomenon of electroosmotic and electrochemical effects on selected local kaolinite soil by subjecting them to different test conditions. This was achieved by varying the following variables;
    a. Surcharges
    b. Voltages

c. Types of electrodes
d. Spacings of electrodes
e. Arrangements of electrodes
f. Connections of electrodes
g. Particles passing different sizes of sieves
h. Types of chemicals
i. Molarities of chemicals

ii. Establishing the best possible combinations of variables given above from (a)-(i) for treatment using both methods on both flat ground and slope conditions.

iii. After conducting the experiments under different conditions, a final conclusion could be drawn as to whether electroosmotic and electrochemical treatments on the selected kaolinite soil produce positive effects or vice versa.

Hence, to achieve the above objectives, this research has adopted the method/sequence of work as given in Figure 2.34 in which the details are given in the methodology section.

At this point, it is important to emphasize here that due to their complexities, this research did not give much weight in distinguishing and isolating the parameters responsible for certain effects on the soil during the course of treatment, but rather concentrating on the main objectives specified above. Of course, by conducting more experiments and further research and also by using more sophisticated equipments, singling out the responsible factors would be undoubtedly possible. However, understanding the general concept of electrochemical process would certainly be helpful in any research on the electrochemical treatment of soil. Barker et al. (2004) have been kind enough to publish a flowchart (Figure 2.35) as an aid in understanding the various processes involving electrochemical treatment.

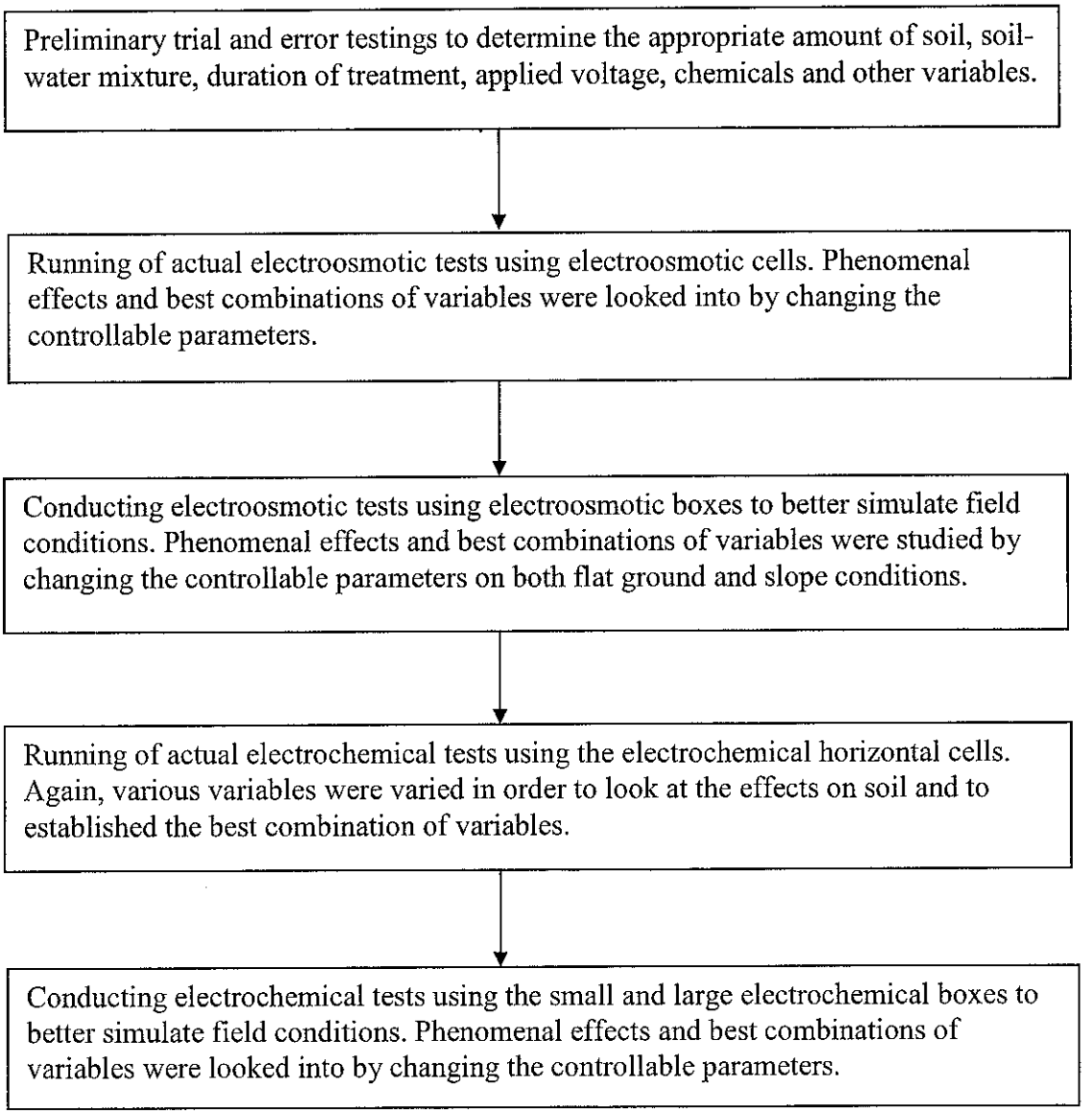


Figure 2.34 Method/sequence of work adopted in research

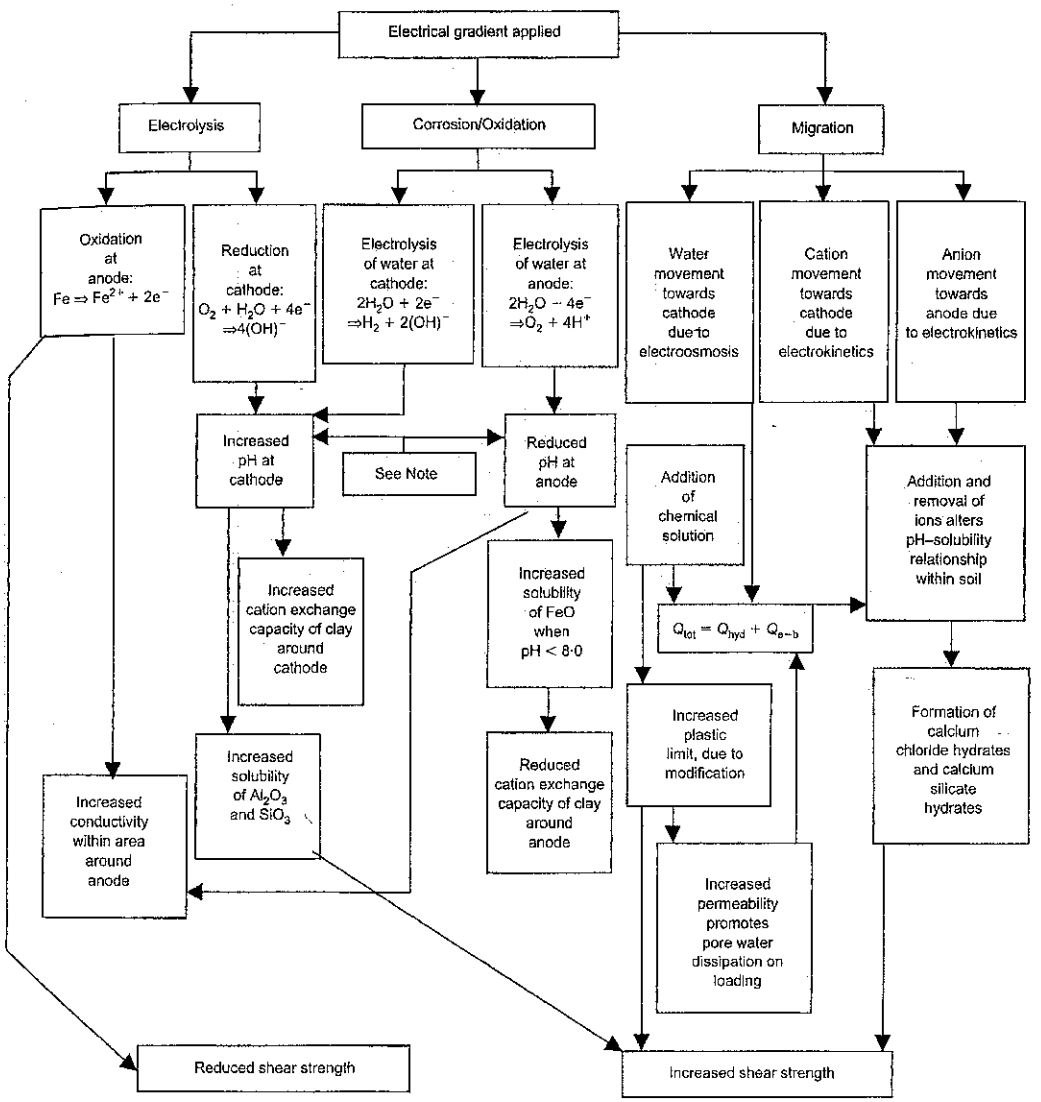


Figure 2.35 Flowchart illustrating various processes involved in electrochemical treatment. Note: Over the range of pH considered, a large increase in hydroxide ion concentration leads to a small increase in pH, whereas a small reduction in hydrogen ions leads to a large decrease in pH (after Barker et al., 2004)

CHAPTER 3
METHODOLOGY

This study primarily focus on investigating electroosmotic and electrochemical effects on Malaysian kaolinite soil and secondarily, concentrates on finding the best possible combination of controllable parameters/variables that supports or enhances the modification and stabilization process especially in electrochemical treatment. For the purpose of conducting the various experiments, specially designed electroosmotic and electrochemical cells and boxes were fabricated. Test samples were placed in these apparatus and were then subjected to different tests conditions such as different chemicals, molarities, voltages, surcharges, electrodes spacings and arrangements, all designed in order to look into the distinct behaviour of kaolinite soil in different tests environments using both the electroosmotic and electrochemical methods of treatment. Therefore, experiments in this research are mainly divided into three sections.

i. Basic physical, chemical and mineralogical tests on soil
ii. Electroosmotic tests
iii. Electrochemical tests

3.1 Basic physical, chemical and mineralogical tests on soil

Transported kaolinite soil samples with average natural moisture content of approximately 39.9% of sandy silt type were obtained near a slope area at a site in Bidor, Perak. The condition of the site is shown in Figure A1, Appendix A and grading curve for the soil is given in Figure A2, Appendix A. A range of laboratory tests were conducted in order to determine the basic physical, chemical and mineral compositions of the soil which were consisted of the following tests;

i. Determination of moisture content
ii. Atterberg's limits
iii. Particle size distribution
iv. Particle density
v. Vane shear
vi. Hydraulic permeability

vii. Electroosmotic permeability[1]

viii. Oedometer

ix. pH

x. Conductivity

xi. X-ray fluorescene (XRF)

xii. X-ray diffraction (XRD)

xiii. Scanning electron microscope (SEM)

xiv. Energy dispersive X-ray (EDX)

xv. Atomic absorption spectrograph (AAS)

3.1.1 Determination of moisture content

All samples were placed in the drying oven at 105°C for a period of at least 24 hours complying to BS 1377: Part 2: 1990.

3.1.2 Atterberg's limits tests

Determinations of the liquid and plastic limits were conducted in accordance with BS 1377: Part 2: 1990.

3.1.3 Particle size distribution

Sieve analysis and hydrometer test were carried out in accordance with BS 1377: Part 2: 1990.

3.1.4 Particle density

Determination of particle density was done by using the small pyknometer methode in accordance with BS 1337: Part 2: 1990.

3.1.5 Vane shear tests

These tests were carried out on the undisturbed samples brought from site and on the remolded sample after every treatment using both the electroosmosis and electrochemical

[1] The electroosmotic permeability is included in the basic properties section for simplicity reason.

method. ELE table top vane shear instruments with motor driven torque applied on the vane were used. All the procedures in these tests were in accordance to BS 1377: Part 7: 1990.

3.1.6 Hydraulic permeability tests

The falling head test was used to determine the coefficient of permeability, k_h, of the kaolinite soil used in this research.

3.1.7 Electroosmotic permeability test

The test was conducted using the modified electroosmotic cell. Three experiments were performed and the average k_e was calculated from equation 2.1.

3.1.8 Consolidation tests

One dimensional consolidation tests using the oedometer was performed on the kaolinite soil samples giving the magnitude and rate of consolidation. The value of coefficient of volume compressibility (m_v), compression index (C_c), and coefficient of consolidation (C_v), were obtained from the oedometer tests which complied to the BS 1377: Part 6: 1990.

3.1.9 pH tests

pH value of the treated and untreated soil samples especially in the electrochemical treatment were taken using a special digital pH meter. The tests conducted were in accordance to BS 1377: Part 3: 1990.

3.1.10 Conductivity tests

The electrical conductivity of the soil was measured using a conductivity meter having a capacity of 5000 μS. The conductivity meter used was of the Myron L type model EP. The soil specimens prepared for measurement of pH were also used for measurement of conductivity.

3.1.11 X-ray fluorescence (XRF) tests

The chemical compositions of the soil specimens before and after treatment were determined using the XRF machine. The XRF testing equipment was equipped with automatic sample feeder for continuous testing.

3.1.12 X-ray diffraction (XRD) tests

XRD tests were performed to compare the mineralogical pattern of treated and untreated soil. The mineralogical analysis was carried out by comparing the XRD patterns with the JCPDS index system.

3.1.12 Scanning electron microscope

Selected treated and untreated soil specimens were brought to the SEM equipment where soil particles were magnified and changes in the shapes, arrangements and fabrics of the particles were observed. The SEM equipment used was of the Leo VP 1430 type.

3.1.13 Energy dispersive X-ray (EDX) tests

The EDX equipment was coupled with SEM detecting the elements in the same sample used for the SEM. The EDX machine was manufactured by Oxford Instrument, model INCA-X-Sight 7533.

3.1.14 Atomic Absorption Spectograph tests

The AAS equipment was used to determine the cation concentrations in the effluent discharged from the treated soil samples in the electrochemical tests.

3.2 Electroosmotic tests

Nine sets of tests were conducted in this series of electroosmotic tests which were divided into three main categories.

1. Tests using soil passing 425 μm sieve size.

Soil passing 425 μm was selected due to the fact that about 80% of the sample passed the 425 μm sieve. It was also because in many other locations in the Tapah-Bidor area,

investigations made by Sulaiman (1991) from the Geological Survey Department of Malaysia showed that most samples had more than 80% of soil passed sieve size 425 μm in sieve analysis. 5 sub-categories of tests were conducted under this 425 μm category.

i. Set 1-electroosmotic cell tests (using only copper electrodes).
ii. Set 2-electroosmotic cell tests (using various types of electrodes).
iii. Set 3-electroosmotic cell tests (futher tests on performance of copper and carbon electrodes using higher voltages).
iv. Set 4-electroosmotic box tests (arrangement Type A, refer to Figure 3.11).
v. Set 5-electroosmotic box tests (comparison between arrangement type A and arrangement type B, refer to Figure 3.12).

2. Tests using soil passing 2 mm sieve size

Soil passing 2mm sieve size was selected as 98% of the sample passed the 2mm sieve size in sieve analysis. Under this category of tests, 3 set of tests were performed.

i. Set 1-electroosmotic cell tests.
ii. Set 2-electroosmotic box tests.
iii. Set 3-electroosmotic tests on slopes.

3. Tests using soil particles passing different sizes of sieves

A different set of experiments were conducted to investigate the effects of electroosmotic and electrochemical on soil particles passing different sizes of sieves.

3.2.1 Electroosmotic apparatus and test set-up

The laboratory set-up of these electroosmotic tests were consisted of the following apparatus.

i. Electroosmotic cell
ii. Electroosmotic box
iii. Instrumentation
iv. Electrical power supply

3.2.1.1 Electroosmotic cell

Details of the electroosmotic cell apparatus are given in Figure 3.1, 3.2, and 3.3.

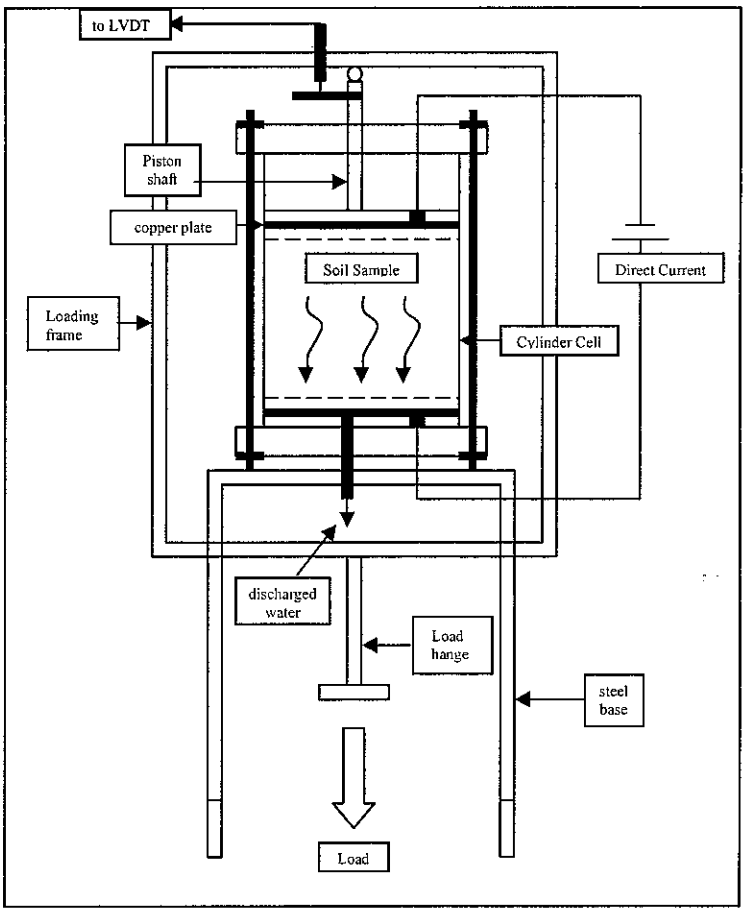


Figure 3.1 Schematic of the electroosmotic tests set-up

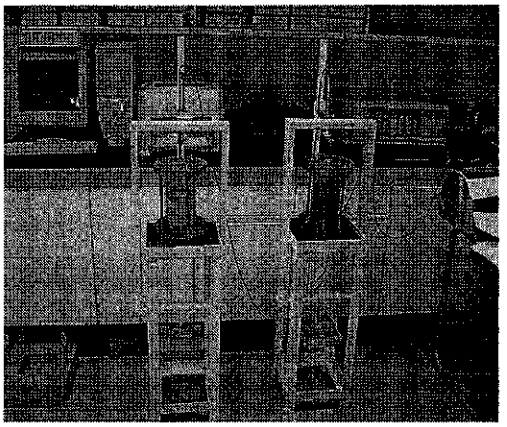


Figure 3.2 Electroosmotic tests set-up

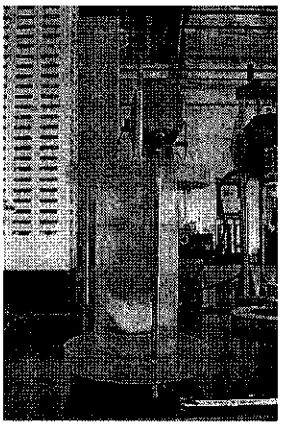


Figure 3.3 Electroosmotic cell

The electroosmotic cell was made from perspex tubing of 100 mm diameter with height of 150 mm. It is equipped with a piston having a steel shaft which glides in a special steel bearing fixed on top of the perspex cylinder ensuring a vertical position so that load applied on the test sample would be 90°. This was important as any slight tilting of the piston shaft could result in leakages at the piston/cell wall interface and also result in the jamming of the piston to the cell wall. A special chemical resistance O-ring fixed in the groove of the piston disc as a seal between the piston and the soil sample beneath. At the base of the soil sample, a groved perspex disc was placed for the purpose of channeling water into a discharging hole at the base of the cell fixed with a 6 mm tubing. Before the cell could be used for conducting tests, the piston and the groved perspex disc were each installed with a perforated copper disc and a non woven geotextile material as shown in Figures 3.4 and 3.5. The diameter of copper disc was about 95 mm with a thickness of 1mm. It contains about twenty five 5 mm holes allowing water to pass through the perforated copper disc into the grooved perspex disc.

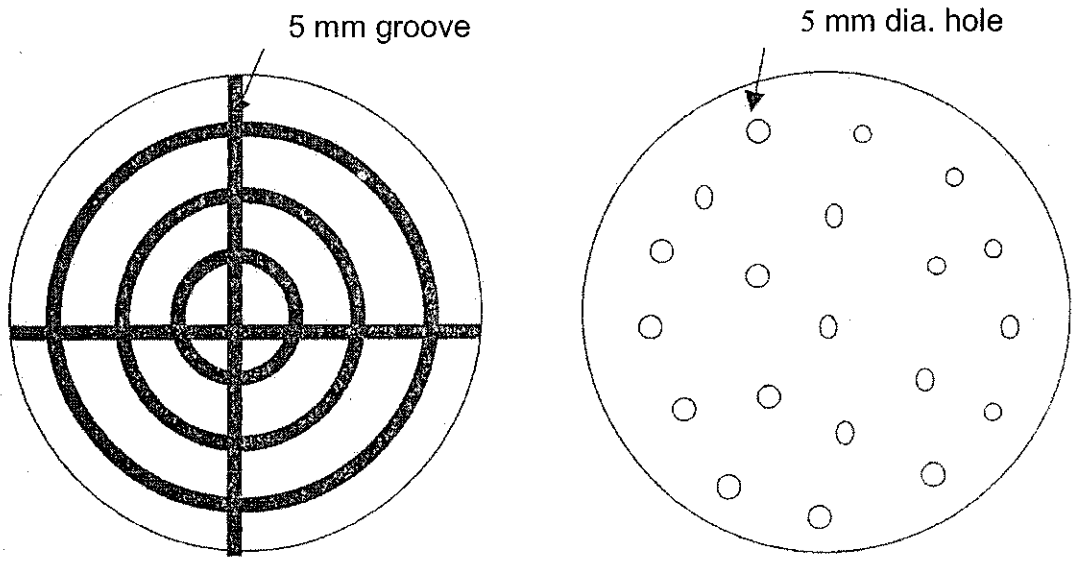


Figure 3.4 Grooved perspex disc and perforated copper disc electrode

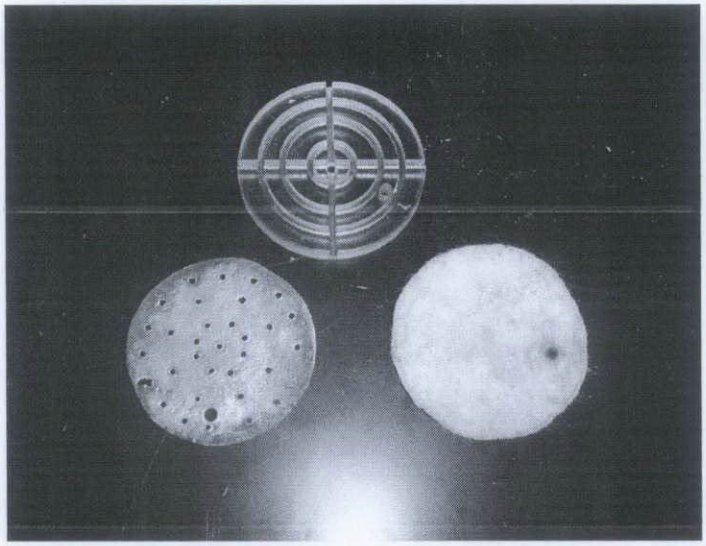


Figure 3.5 Grooved perspex disc, perforated copper disc electrode, and geotextile separator

The copper disc sandwiched between the soil sample and perspex disc served to conduct current from the power supply through the soil sample. The function of the geotextile material was to act as a separator between the soil particles and the grooved perspex disc to ensure no loss of soil particles which might pass through into the discharging hole. Both the copper disc and geotextle were secured to the piston and grooved perspex disc tightly with metal screws which were connected with wires to conduct electrical current. Small 5 mm holes were also made through the piston and top cover of the perspex cell to allow escape of any gas formed during the electroosmotic process.

Loading/surcharge was imposed on the soil sample by means of a loading frame and transmitted through the piston. A set of desired weights were hanged on the load hanger serving as the surcharge as shown in Figures 3.1 and 3.2. A steel ball was placed in between the loading frame and the steel shaft of the piston acting as a non-rigid connection ensuring vertical transmission of loading. The electroosmotic cell was then placed on a steel base as shown.

3.2.1.2 Electroosmotic box

The apparatus was consisted of three major parts, the main 375 x 225 x 250 mm container box, 375 x 225 x 12 mm cover plate, and 325 x150 x150 load platform. Only the load platform was made from steel and the rest were made from perspex material. Figures 3.6 and 3.8 show the diagram and picture of the apparatus. 10 mm holes were made through the base of the container box and the cover plate. They were vertically aligned with each other for the purpose of placing stainless steel rods through the cover plate and directly above the holes at the base of the box. The rigid steel load platform was designed in such a way so that it could sustain the load applied on it and avoiding being in contact with the stainless steel rods to prevent short circuit. The container box was fabricated so as to be leak-proof and this was done by applying special epoxy on all joints. As a precaution, every joints of the box were screwed together to avoid breakage of joints due to high surcharge on the soil sample. One grove of size 25 mm wide and 5mm thick were made at the middle of each end in the wall of the perspex box as shown in Figures 3.6 and 3.8 where special metal railings were screwed to the groves. The cover plate was attached to linear bearings at both its end where both bearings along with the cover plate glides smoothly in the railing. This smooth gliding was very important so as to ensure vertical and uniform distribution of surcharge on the soil sample and to avoid the cover plate being jammed to the wall of the box during settlement of the soil sample. The set up of the experiment is shown in Figure 3.7.

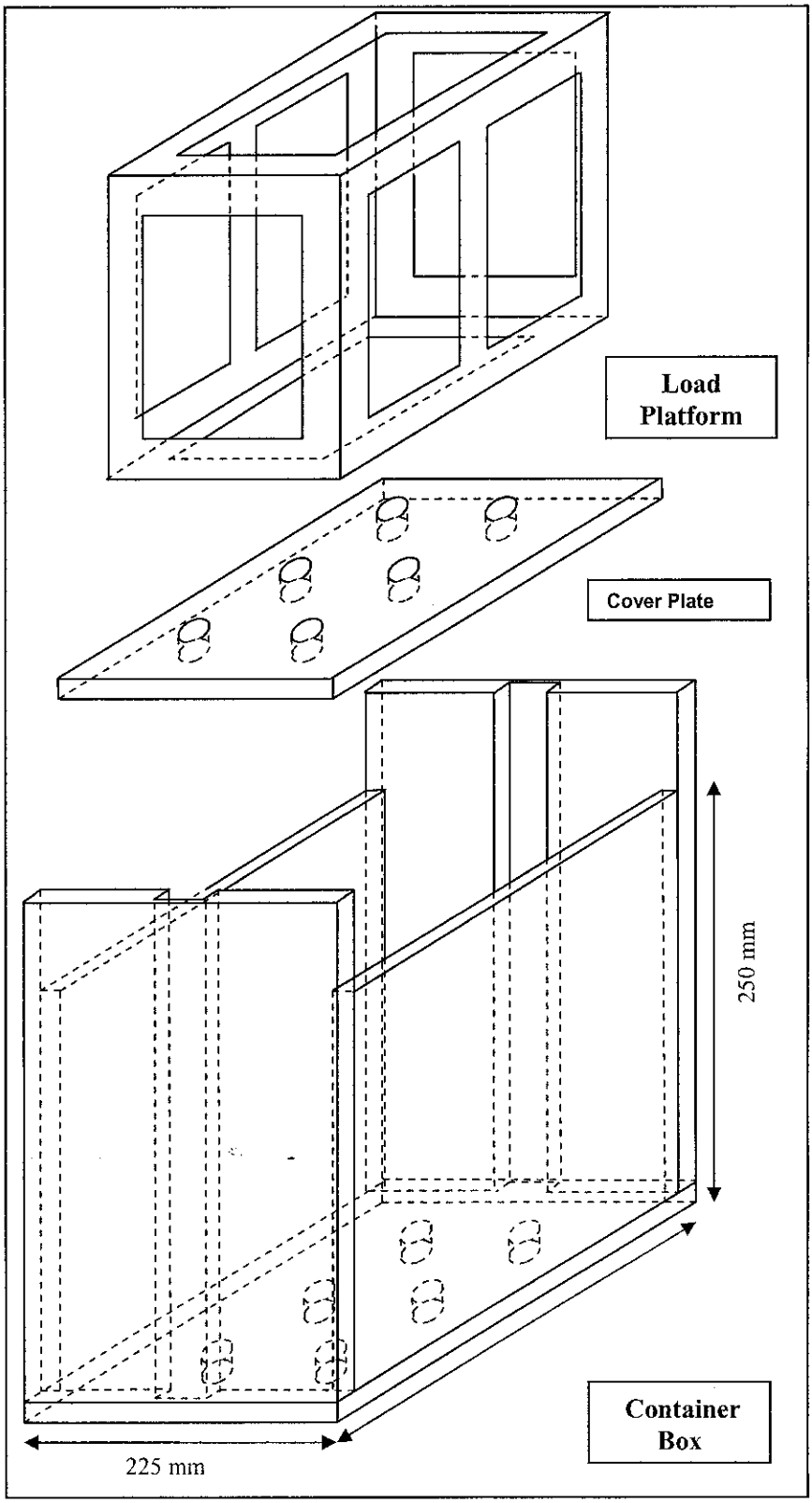


Figure 3.6 Electroosmotic box system

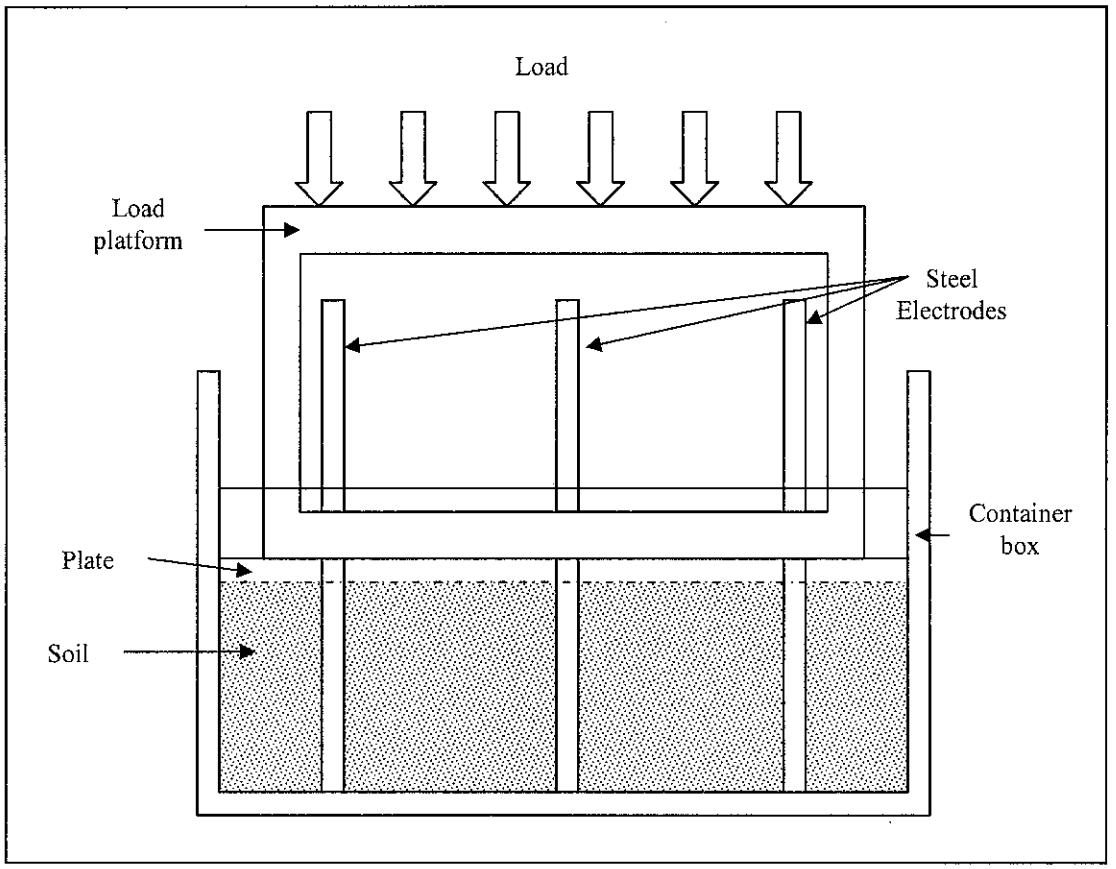


Figure 3.7 Set-up of the electroosmotic box tests

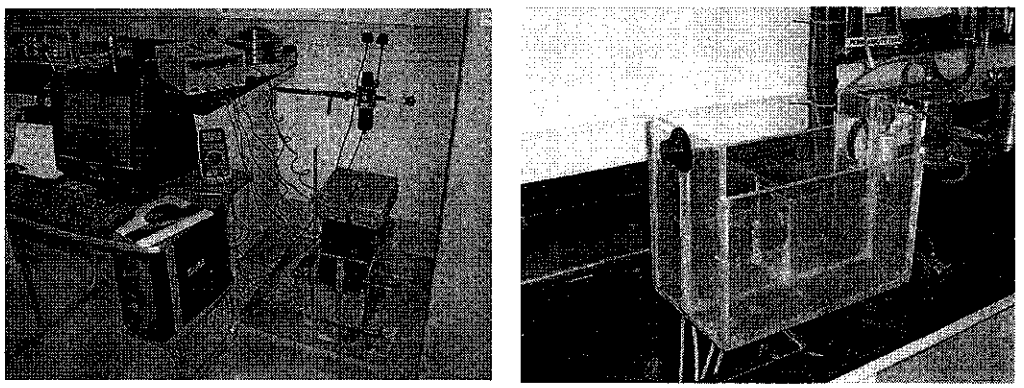


Figure 3.8 Set-up of the electroosmotic box tests and electroosmotic box

3.2.1.3 Instrumentation

For the electroosmotic cell, a linear vertical distance tranducer (LVDT) was placed on a plate attached to the steel shaft of the piston as shown in Figure 3.1. It was used to measure vertical settlement of the soil sample during consolidation. For the electroosmotic box, the LVDT was attached to a retort stand and the LVDT plunger end would rest on the cover plate measuring settlement during treatment. Both the LVDTs in the cell and box tests were connected to an ELE data logger (Figure 3.9) to automatically record settlement data while running the test. Current and voltage readings were taken with a Fluke multimeter with logging capacity in order to log current value throughout the test period.

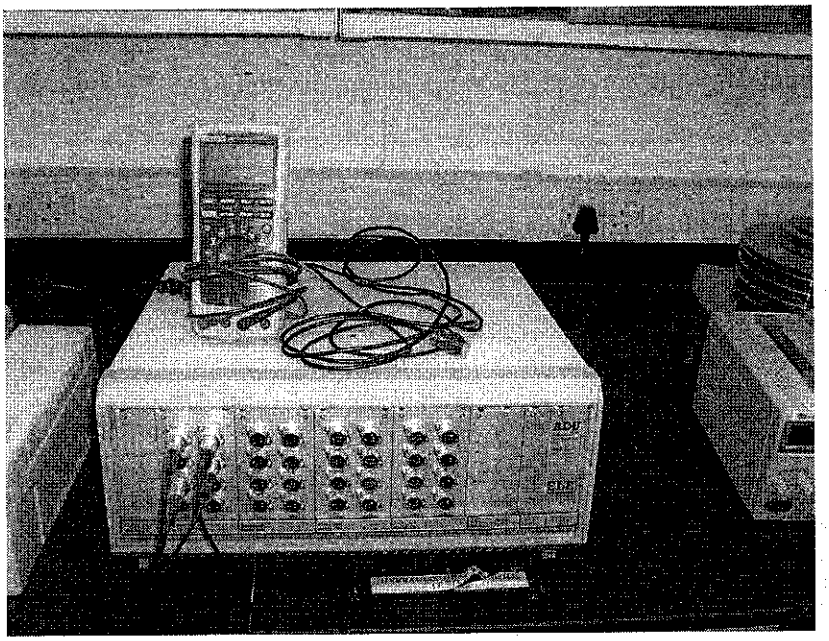


Figure 3.9 ELE data logger and Fluke data logging multimeter

3.2.1.4 Power supply

An important equipment in any electrokinetic treatment, the variable power supply unit used had dual output. The maximum capacity of the unit was 300 Volt with maximum current of 1 Amp. The unit also had digital display for easy checking of voltage and current variations. Single core copper wire of 1mm diameter was used as the power

supply lead to the electrodes. Uninterrupt power supply (UPS) unit was also used to provide temporary current supply in case of black out. Both the equipments are shown in Figure 3.10.

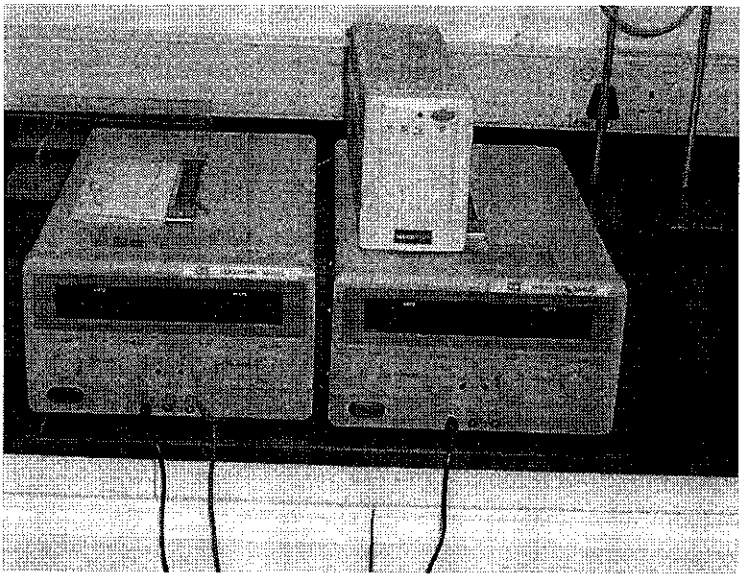


Figure 3.10 Variable power supplies and UPS

3.2.2 Sample preparation

The methods used to prepare samples in the electroosmotic cell and box tests were basically the same except for the change in amount/weight of soil and distilled water used in the sample preparation. They were carried out as follows;

i. After putting together the cell apparatus, the test sample was prepared by mixing dry soil with distilled water to form a slurry mixture having the desired initial moisture content. The mixed slurry was wet enough to allow thorough mixing without the entrainment of air into the soil. The mixture was then mixed in a stainless steel bowl using a bench mixer and then kept for at least 24 hours to make it more homogeneous.

ii. A layer of silicon grease was applied on the interior wall of the cell before the placement of soil. The grease was applied to prevent formation of film of water at the interface between the soil sample and the cylinder. Formation of the film of water

would short circuit the system in the sense that electrical current would flow through the film instead of the soil rendering the electroosmotic process ineffective. The grease also served as a lubrication to reduce friction between the piston and the wall of the cell.

iii. The soil was then placed in the cell or box in layers of about 50 mm thick and rodded to remove entrapped air. The procedure was repeated until all the soil was placed.

iv. For the electroosmotic cell tests, the cylinder was then tightly closed with the top cover by tightening the three tie rods at both the ends with wingnuts.

v. For the electroosmotic box, the cover plate was then put in place by sliding the linear bearing at both ends into the respective vertical railings. A layer of geotextile was placed at the base of the box acting as a separator.

3.2.2.1 Precautionary measures

i. The soil was placed carefully in the cylinder so that it did not stick to the internal wall. This was to ensure smooth gliding of the piston in the cylinder.

ii. Logging of the settlement was activated immediately before putting surcharge on the sample.

iii. Area of experiment was barricaded to avoid touching of the electroosmotic cells and LVDTs.

3.2.2.2 Measurement taken during and after tests

The electroosmotic consolidation tests were started by applying the current concurrently with the application of surcharge and opening of the drainage outlet. Simultaneously, logging of the vertical settlement was automatically done using the ADU and the current was recorded manually and automatically.

Therefore during the tests, two types of readings were taken;

i. Settlement/consolidation.

ii. Variations of current.

After completing each experiment, the following tests were conducted on the soil sample;

i. Vane shear test.

ii. Determination of moisture content.

It should be noted here that any additional test or procedure conducted besides those given above would be mentioned separately in the individual test section.

3.2.3 Electroosmotic cell tests – soil passing 425 µm sieve

Three categories of tests were performed under this electroosmotic cell tests. The three categories were;

i. Tests using only copper electrodes.

ii. Test using different types of electrodes.

iii. Additional 100 and 200 volts tests using carbon electrodes.

It should be noted here that in general, most of the tests conducted in this research used copper and stainless steel electrodes. The reasons being were due to the fact that both materials have been used and proved to be effective in many treatments involving electrokinetic process, there are readily available in the market and there are relatively non- expensive.

3.2.3.1 Tests with only copper electrodes

The summary of tests is given in the Table 3.1.

Table 3.1 Summary of electroosmotic cell tests –soil passing 425 µm sieve

Test no.	Wt. of soil (g)	Wt. of water (g)	Initial moisture content (%)	Surcharge (kPa)	Voltage (V)	Test period (days)
1	750	375	50	10	0	7
2	750	375	50	20	0	7
3	750	375	50	30	0	7
4	750	375	50	20	10	7
5	750	375	50	20	20	7
6	750	375	50	20	30	7
7	750	375	50	20	100	7
8	750	375	50	20	200	7

- Initial moisture content for all tests in this set was 50% which was approximately 1.5 times the liquid limit. Moist unit weight of soil was $1.7x10^3$ kg/m^3.
- Only copper electrodes were used in these tests.

3.2.3.2 Tests using various types of electrodes

All tests conducted in this series are summarized below.

Table 3.2 Tests using various types of electrodes

Test no.	Types of electrodes	Wt. of soil (g)	Wt. of water (g)	Initial moisture content (%)	Sur-charge (kPa)	Voltage (V)	Test period (days)
1	brass	750	375	50	20	30	7
2	aluminium	750	375	50	20	30	7
3	steel	750	375	50	20	30	7
4	carbon	750	375	50	20	30	7
5	copper	750	375	50	20	30	7

- Initial moisture content was 50%.
- Different material types of electrodes were used as shown in Table 3.2. The materials specifications are in accordance with UNS standard given in Table A2.

3.2.3.3 Additional tests using carbon electrodes

Table 3.3 Summary of additional tests using carbon electrodes

Test no.	Wt. of soil (g)	Wt. of water (g)	Initial moisture content (%)	Surcharge (kPa)	Voltage (V)	Test period (days)
1	750	375	50	20	100	7
2	750	375	50	20	200	7

- Initial moisture content was 50% and only carbon electrodes were used.
- Results obtained were compared with tests using copper electrodes as given in Chaper 4.

3.2.4 Electroosmotic box tests-soil passing 425 μm sieve

The electroosmotic cell tests were simpler method of experiment in the sense that they used less amount of soil, less loading and took less time in preparation and setting up. Several trial and error and repeated tests could be done without causing much decrease in the processed sample, and at the same time consumed less time and labour. These trial and error and repeated tests were necessary in order to initially establish the appropriate combinations of surcharge, voltages, amount of soil etc. which could produce reliable results in preliminary understanding the behavior of electroosmotic treatment on the Bidor kaolinite soil. Once the appropriate combinations of the above mentioned variables were established through the preliminary cell tests, electroosmotic box tests were then carried out due to their ability to better simulate field condition. The box tests were also a mean to double check the reliability of the experiments conducted using the cell tests.

Two sets of tests with different electrodes arrangements were conducted;

i. Type A.

ii. Type B.

3.2.4.1 Main tests using electrodes arrangement Type A

Table 3.4 Summary of main tests using electrodes arrangement Type A

Test no.	Wt. of soil (kg)	Wt. of water (kg)	Initial moisture content (%)	Surcharge (kPa)	Voltage (V)	Test period (days)
1	10	5	50	2.5	0	7
2	10	5	50	5	0	7
3	10	5	50	10	0	7
4	10	5	50	5	10	7
5	10	5	50	5	20	7
6	10	5	50	5	30	7
7	10	5	50	5	100	7
8	10	5	50	5	200	7

- Initial moisture content was 50%.
- Stainless steel electrodes were used in the experiments.
- The arrangement of electrodes is given in Figure 3.11.

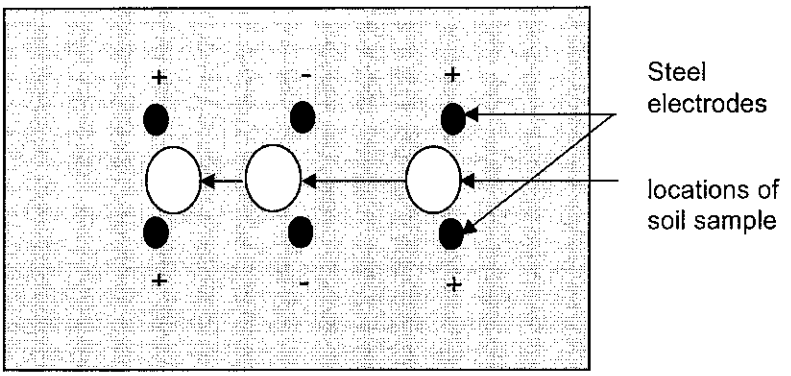


Figure 3.11 Arrangement of electrodes and locations of extruded samples (Type A)

- Spacing of electrodes was approximately 125 mm.
- Discharging points of water were at both the cathodes.
- After treatment, 3 samples were extruded using sampling tube at locations shown in the same Figure 3.11 for determination of shear strength and moisture content.

3.2.4.2 Test using electrodes arrangement Type B

Table 3.5 Summary of tests using electrodes arrangement Type B

Test no.	Wt. of soil (kg)	Wt. of water (kg)	Initial moisture content (%)	Surcharge (kPa)	Voltage (V)	Test period (days)
1	10	5	50	5	30	7
2	10	5	50	5	100	7
3	10	5	50	5	200	7

- Initial moisture content was 50%.
- Stainless steel electrodes were used in the experiments.
- The arrangement of electrodes is given in Figure 3.12.

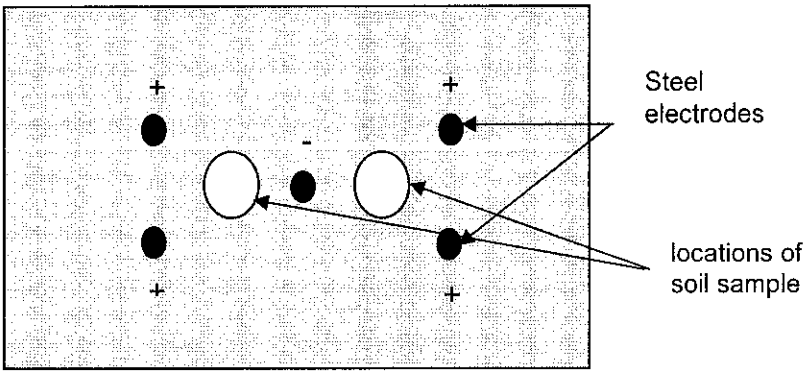


Figure 3.12 Arrangement of electrodes and locations of extruded samples (Type B)

- Discharging point of water was at the cathode in the centre.
- After treatment, two samples were extruded at location given in Figure 3.12 for further testings.

3.2.5 Electroosmotic cell tests-soil passing 2 mm sieve

Another set of experiments were conducted to look into the effect of bigger particle size when subjected to electroosmotic treatment. The summary of the tests is given in Table 3.6.

Table 3.6 Summary of electroosmotic cell tests – soil passing 2 mm sieve

Test no.	Wt. of soil (g)	Wt. of water (g)	Initial moisture content (%)	Surcharge (kPa)	Voltage (V)	Test period (days)
1	750	485	65	10	0	7
2	750	485	65	20	0	7
3	750	485	65	30	0	7
4	750	485	65	20	10	7
5	750	485	65	20	20	7
6	750	485	65	20	30	7

- Initial moisture content was 65%.

- Only copper electrodes were used at both the anode and cathode.
- After performing vane shear test, the sample were then sliced into approximately 6 layers of 15 mm each and placed in the drying oven for measurement of moisture content. Variations of moisture content along the sample were then recorded.

3.2.6 Electroosmotic box tests-soil passing 2 mm sieve

Table 3.7 Summary on electroosmotic box tests-soil passing 2 mm sieve

Test no.	Wt. of soil (kg)	Wt. of water (kg)	Initial moisture content (%)	Surcharge (kPa)	Voltage (V)	Test period (days)
1	10	6.5	65	2.5	0	7
2	10	6.5	65	5	0	7
3	10	6,5	65	10	0	7
4	10	6.5	65	5	10	7
5	10	6.5	65	5	20	7
6	10	6.5	65	5	30	7

- Initial moisute content was 65%.
- Stainless steel electrodes were used.
- Arrangement of electrodes and locations of extruded samples are given in Figure 3.13.
- Sample were then sliced into 6 layers from top to bottom and then placed in drying oven for measurement of moisture content. Variations of moisture content along the sample were then recorded.

3.2.7 Electroosmotic treatment on slopes-soil passing 2 mm sieve

A set of tests simulating treatment in slope conditions was carried out using the electroosmotic box. This category of experiments was consisted of two sets of tests.

i. Electrodes connection Type A

ii. Electrodes connection Type B

3.2.7.1 Main tests using normal connection of electrodes Type A

Table 3.8 Summary of tests using connection of electrodes Type A

Test no.	Wt. of soil (g)	Wt. of water (g)	Initial moisture content (%)	Surcharge (kPa)	Voltage (V)	Test period (days)
1	10	5.5	55	0	0	7
2	10	5.5	55	0	0	12
3	10	5.5	55	0	0	17
4	10	5.5	55	0	10	7
5	10	5.5	55	0	20	7
6	10	5.5	55	0	30	7

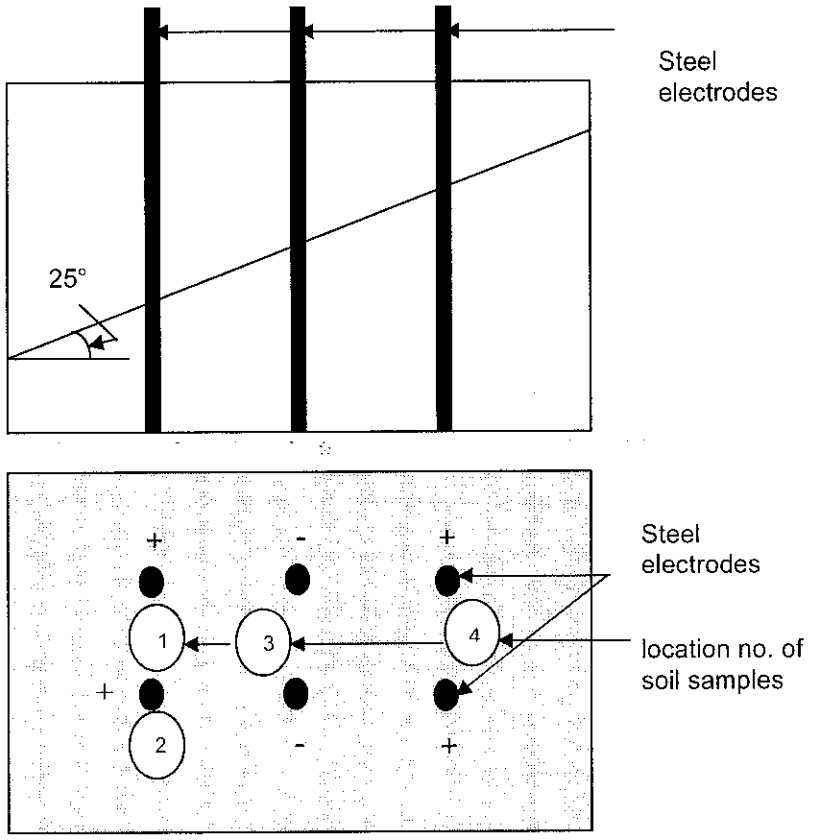


Figure 3.13 Slope condition, electrode arrangement and locations of samples

- Initial moisture content was 55%.
- Stainless steel electrodes were used.
- The slope was constructed at a sloping angle of 25° as shown in Figure 3.13 .
- Arrangement of electrodes is shown in Figure 3.13.
- This Type A connections of electrodes to the power supply is shown in Figure A3, Appendix A.
- Locations 1, 2, 3, and 4 where samples were extruded for testings are also shown in Figure 3.13.
- The extruded samples were then sliced in 5 sections each and placed in the drying oven for measurement of moisture content. Variations of moisture content along the sample were then recorded.

3.2.7.2 Tests using different electrodes connection Type B

Only one additional test was carried out for this type of electrodes connection.

Table 3.9 Additional test using electrodes connection Type B

Test no.	Wt. of soil (g)	Wt. of water (g)	Initial moisture content (%)	Surcharge (kPa)	Voltage (V)	Test period (days)
1	10	5.5	55	0	20	7

- Initial moisture content was 55%.
- Same type of stainless steel electrodes was used.
- The slope was constructed at a 25° angle.
- Arrangement of electrodes is as shown in Figure 3.13.
- Locations 1, 2, 3, and 4 where samples were extruded for testings are as shown in Figure 3.14.
- This Type B connection of electrodes to the power supply is shown in Figure A4, Appendix A.

3.2.8 Electroosmotic cell tests-soil passing various sieve sizes

The results are given as below.

Table 3.10 Summary of cell tests-soil passing various sieve sizes

Test no.	Particles passing sieve size	Wt. of soil (g)	Wt. of water (g)	Initial moisture content (%)	Sur-charge (kPa)	Voltage (V)	Test period (days)
1	Unsieved	750	375	50	10	30	7
2	2.00 mm	750	375	50	10	30	7
3	425 μm	750	375	50	10	30	7
4	150 μm	750	375	50	10	30	7
5	63 μm	750	375	50	10	30	7

- Initial moisture content was 50%.
- Only copper electrodes were used.

3.2.9 Electroosmotic box tests-various electrode spacings

A different box and set-up were designed for this set of experiment. The purpose of these experiments was to look into the effect of various spacings of electrodes in electroosmotic treatment.

Table 3.11 Summary of tests for various electrode spacings

Test no.	Spacings of electrodes (mm)	Wt. of soil (g)	Wt. of water (g)	Initial moisture content (%)	Sur-charge (kPa)	Voltage (V)	Test period (days)
1	450	750	375	50	0	30	7
2	225	750	375	50	0	30	7
3	112.5	750	375	50	0	30	7

- Only stainless steel electrodes were used.

3.3 Electrochemical tests

The main difference between the electroosmotic and electrochemical treatment lies in the fact that chemical was injected into the system during treatment in electrochemical method. Four sets of tests were conducted under this electrochemical tests category. In anticipation of its better ability in modifying and stabilizing soil, special focus was given to this part. Extended analysis was carried out on certain tests to better understand the nature of this electrochemical process.

Four types of chemicals were basically used in the electrochemical tests. They were $CaCl_2$, $Ca(NO_3)_2$, $Ca(OH)_2$ and $Mg(OH)_2$. Calcium chloride and calcium hydroxide were chosen because they are currently widely used in non-electrokinetic soil stabilization. Calcium nitrate and magnesium hydroxide have been used by researchers in laboratory non-electrokinetic soil stabilization and thus study on their effectiveness in electrokinetic treatment of local kaolinite soil was conducted.

3.3.1 Electrochemical apparatus and test set-up

The laboratory set-up of these electrochemical tests consists of the following apparatus;

i. Electrochemical horizontal cell.
ii. Electrochemical box, small and large.
iii. Fluid/chemical supply system.
iv. Instrumentation.
v. Electrical power supply.

3.3.1.1 Electrochemical horizontal cells

Details of the electrochemical cell apparatus are given in Figure 3.14 and 3.15. Instead of the vertical set-up of the cells in electroosmotic tests, the cells used in the electrochemical treatment were horizontal. The cells were made from the same type of perspex tube of 100 mm diameter with a length of 200 and 275 mm. They were each equipped with a piston (at the cathode's end) having a steel shaft to allow testing of samples with different lengths.

They were also provided with a liquid/chemical chamber close to the anode where liquid was injected through the 3 mm hole on the top side of the cell wall. Special attention was given in the construction of the liquid chamber where both the perspex disc used forming the liquid chamber were properly sealed with chemical resistance O-rings to prevent leakage of fluid/chemical during treatment. The piston disc near the cathode's end of the soil sample was also sealed ensuring all fluid to be discharged only through the hole and tube at the bottom of the piston disc as shown in Figure 3.15. Geotextile material and perforated copper disc were then securely attached to both the perspex disc as shown in the same figure.

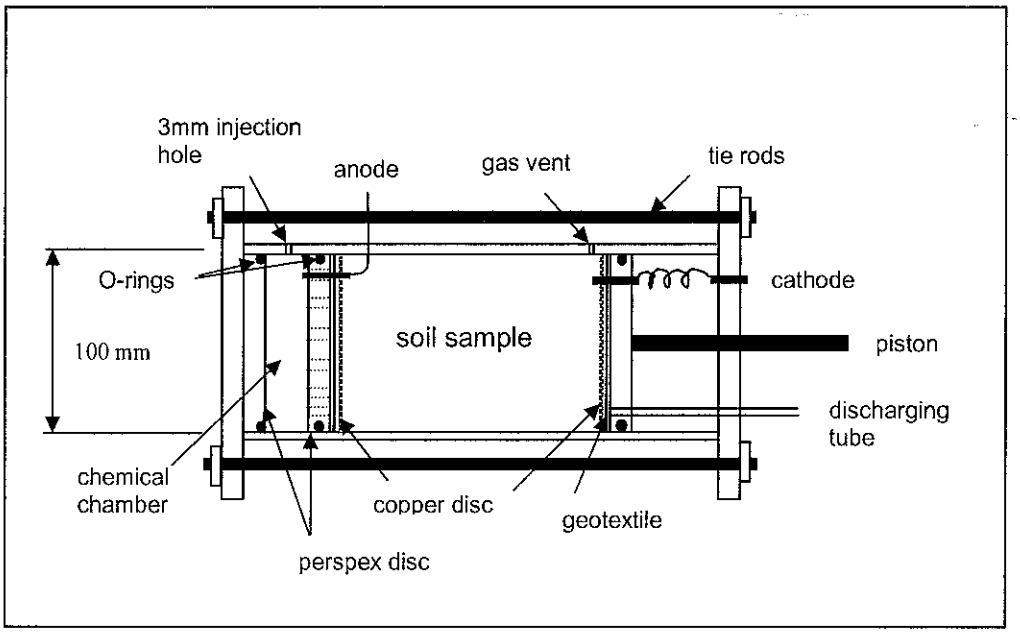


Figure 3.14 Electrochemical horizontal cell

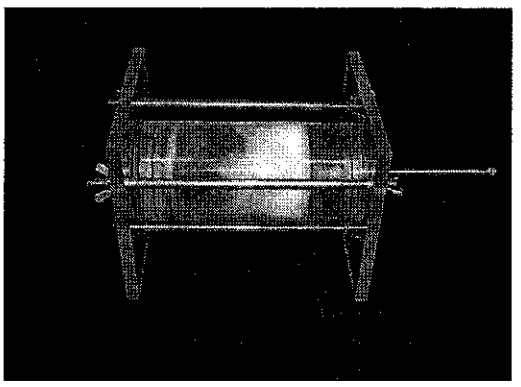


Figure 3.15 Horizontal cell

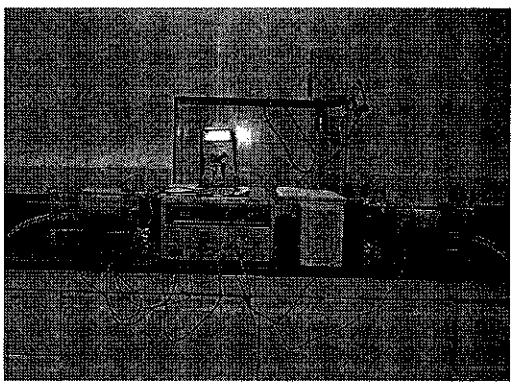


Figure 3.16 Set-up of tests

3.3.1.2 Electrochemical boxes

The electrochemical box set-up was much simpler than the set-up for the electroosmotic box because no surcharge was imposed on the soil sample and no settlement reading was taken. The box set-up consisted of only the same main container box as shown in Figure 3.6. The sizes of the boxes used were 375 x 225 x 250 mm (same as the container box for electroosmotic tests) and a larger size box having the dimension of 750 x 325 x 425 mm. A modification was made on the box utilized for electrochemical slope treatment incorporating a stopper as shown in Figure 3.17. It was done so to increase the angle of the slope and also to provide better drainage system.

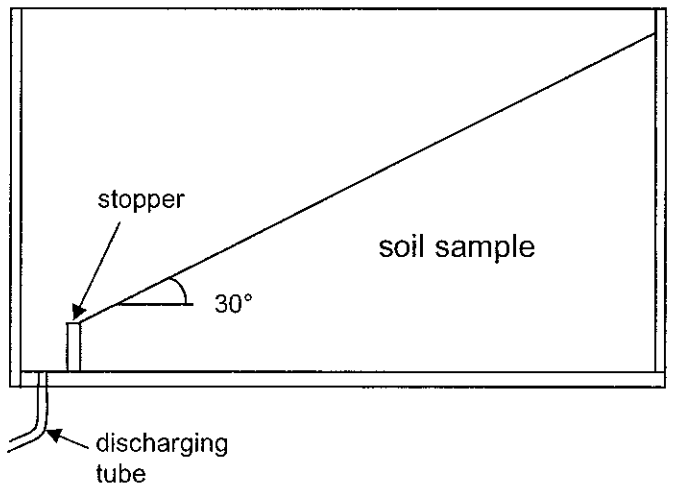


Figure 3.17 Modification of box for electrochemical slope treatment

3.3.1.3 Fluid/chemical supply system

In some of the electrochemical tests, the fluid/chemical was introduced into the system by flowing the fluid/chemical from chemical resistant plastic bottles attached to a retort stand as shown in Figure 3.18. The chemical contained in the plastic bottle flowed down the tube joining to the 25 mm diameter copper tubing serving as the anode as shown in Figure 3.18.

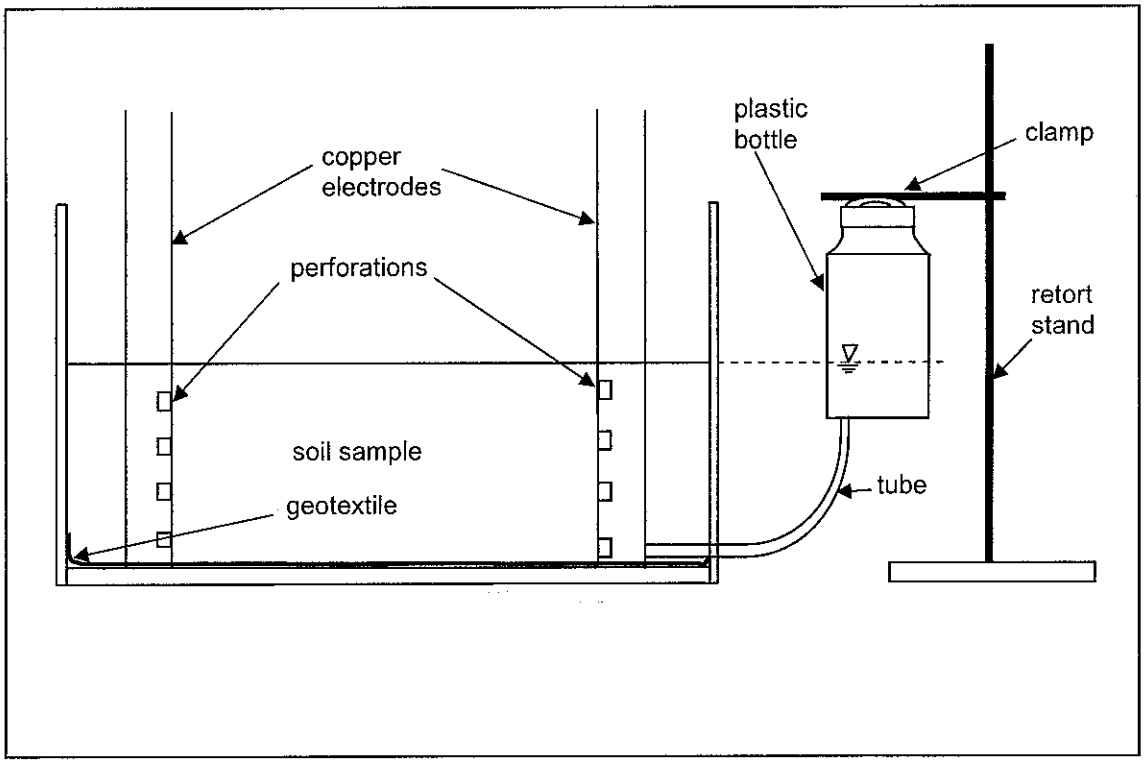


Figure 3.18 Fluid/chemical supply system

3.3.1.4 Instrumentation

Since no settlement reading was taken, the only instrument attached to the electrochemical set-up was the Fluke multimeter with logging capacity.

3.3.1.5 Power supply

The power supply for these experiments was the same as given in section 3.2.1.4.

3.3.2 Sample preparation

Basically, the methods used to prepare samples in these electrochemical tests were the same for the electroosmotic tests as stated in section 3.2.2. All tests used only soil particles passing 2mm sieve size.

3.3.2.1 Precautionary measures

i. Due to the corrosive nature of the electrochemical tests, all connections exposed to the soil and chemical were thoroughly seal with silicone sealant to avoid corrosion.

ii. The electrochemical cell was susceptible to deformation and breakage when temperature became extremely high. Therefore when using 100 volts or more especially when using $CaCl_2$ and $Ca(NO_3)_2$, special monitoring were tended due to the development of high temperature.

iii. The chemical resistant O-ring seals were always checked for leakage especially those within the chemical chamber. This was to ensure smooth supply of fluid/chemical into the system.

3.3.2.2 Measurements taken during and after tests

After sample preparation and setting-up of the testing apparatus, current were applied and simultaneously the chemical or distilled water were induced into the system.

During treatment, depending on the test, one or more of the following parameters were recorded.

i. Current variation.

ii. Variation of voltage along the sample.

After a particular test was completed, the following tests were conducted on the soil sample;

i. Vane shear test.

ii. Determination of moisture content.

Any additional tests carried out were mentioned separately in the individual test section.

3.3.3 Electrochemical horizontal cell tests

The summary for all the tests in this set of experiments is given in Table 3.12.

Table 3.12 Electrochemical horizontal cell tests

Test no.	Type of chemical and molarity	Wt. of soil (kg)	Wt. of water (kg)	Wt. of fluid in chamber (kg)	Total moisture content (%)	Voltage (V)	Test period (days)
1	1mol $CaCl_2$	1.0	0.4	0.1	50	30	7
2	2mol $CaCl_2$	1.0	0.4	0.1	50	30	7
3	3mol $CaCl_2$	1.0	0.4	0.1	50	30	7
4	1mol $CaCl_2$	1.0	0.4	0.1	50	100	7
5	2mol $CaCl_2$	1.0	0.4	0.1	50	100	7
6	Dist. water	1.0	0.4	0.1	50	30	7
7	Dist. water	1.0	0.4	0.1	50	100	7
8	1mol $Ca(OH)_2$	1.0	0.4	0.1	50	30	7
9	1mol $Ca(NO_3)_2$	1.0	0.4	0.1	50	30	7
10	2mol $Ca(OH)_2$	1.0	0.4	0.1	50	30	7
11	1mol $Ca(NO_3)_2$	1.0	0.4	0.1	50	100	7
12	1mol $Ca(OH)_2$	1.0	0.4	0.1	50	100	7
13	1mol $Mg(OH)_2$	1.0	0.4	0.1	50	30	7

- Only copper electrodes were used
- After treatment, some portions of selected test samples were sent for XRD, XRF, and SEM analysis.
- 0.4 kg of distilled water was initially mixed with the 1kg kaolinite soil.
- Remaining 0.1kg of distilled water was mixed with chemicals given in Table 3.12 forming solution with the desired molarity injected in the chemical chamber.

3.3.4 Electrochemical box tests-125 mm spacing

This set of electrochemical experiments was conducted to better simulate field condition. The summary of all the tests is given in Table 3.13.

Table 3.13 Electrochemical box tests-125 mm electrode spacing

Test no.	Type of chemical and molarity	Wt. of soil (kg)	Wt. of water (kg)	Wt. of fluid in bottle (kg)	Total moisture content (%)	Voltage (V)	Test period (days)
1	1mol $CaCl_2$	10	4.0	1.0	50	30	7
2	1mol $Ca(NO_3)_2$	10	4.0	1.0	50	30	7
3	1mol $Ca(OH)_2$	10	4.0	1.0	50	30	7
4	1mol $Mg(OH)_2$	10	4.0	1.0	50	30	7
5	Dist. water	10	4.0	1.0	50	30	7
6	1mol $CaCl_2$	10	4.0	1.0	50	100	7
7	1mol $Ca(NO_3)_2$	10	4.0	1.0	50	100	7
8	1mol $Ca(OH)_2$	10	4.0	1.0	50	100	7
9	Dist. water	10	4.0	1.0	50	100	7

- Copper electrodes were used in the tests.
- The arrangement of electrodes is given in Figure 3.19.
- The locations where samples were extruded using the sampling tube are also given in Figure 3.19.
- Approximately same amount of chemical solution was injected into all the four hollow copper electrodes each time of topping up.
- Topping up of the chemical solution were done up to the level of the top surface of soil until all the chemical solution were consumed.
- 4.0 kg of distilled water was initially mixed with the 10 kg soil.

- Remaining 1.0 kg of distilled water was mixed with chemicals given in Table 3.13 forming solution with the desired molarity which was then placed in the plastic bottle.

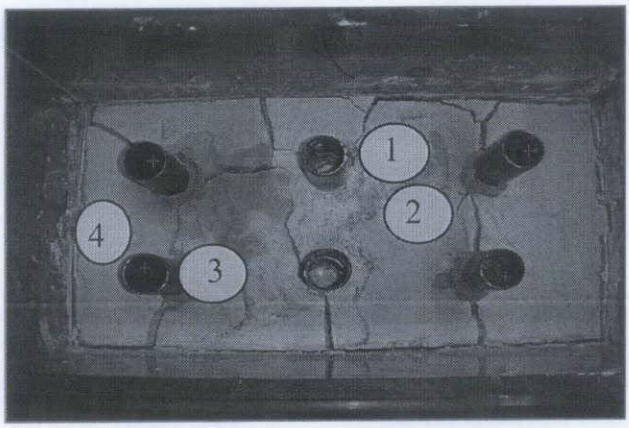


Figure 3.19 Arrangement of electrodes and locations of extruded samples

3.3.5 Electrochemical box tests-150, 300, and 600 mm spacings

A more elaborate analysis was carried out in this set of experiments especially on the 300 mm spacing. Apart from the normal tests, additional tests were conducted in the effort to better understand the behavior of this kaolinite soil when subjected to electrochemical treatment. Only $CaCl_2$ and distilled water were used in these experiments.

Table 3.14 Electrochemical box tests-150, 300, and 600 mm spacings

Spacing (mm) -	Type of chemical and molarity	Wt. of soil (kg)	Wt. of water (kg)	Wt. of fluid in bottle (kg)	Total moisture content (%)	Voltage (V)	Test period (days)
150	1mol $CaCl_2$	2.5	1.0	0.25	50	100	7
150	Dist. water	2.5	1.0	0.25	50	100	7
300	1mol $CaCl_2$	5.0	2.0	0.50	50	100	7
300	Dist. water	5.0	2.0	0.50	50	100	7
600	1mol $CaCl_2$	10	4.0	1.0	50	100	7
600	Dist. water	10	4.0	1.0	50	100	7

- The test using 600 mm electrode spacing was conducted in the large electrochemical box as shown in Figure 3.20.
- Hollow copper tubings were used as the electrodes.

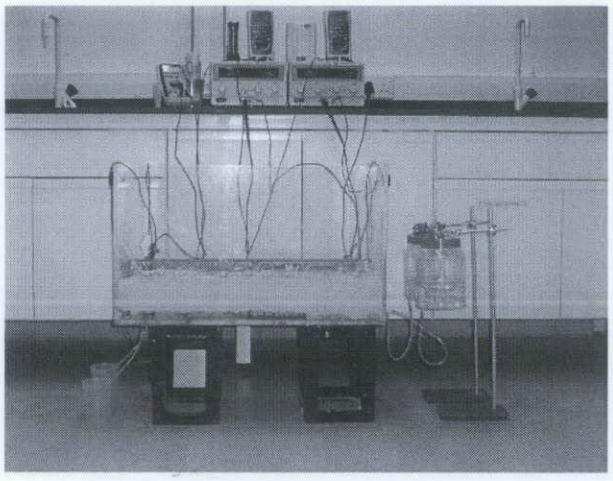


Figure 3.20 Large electrochemical box

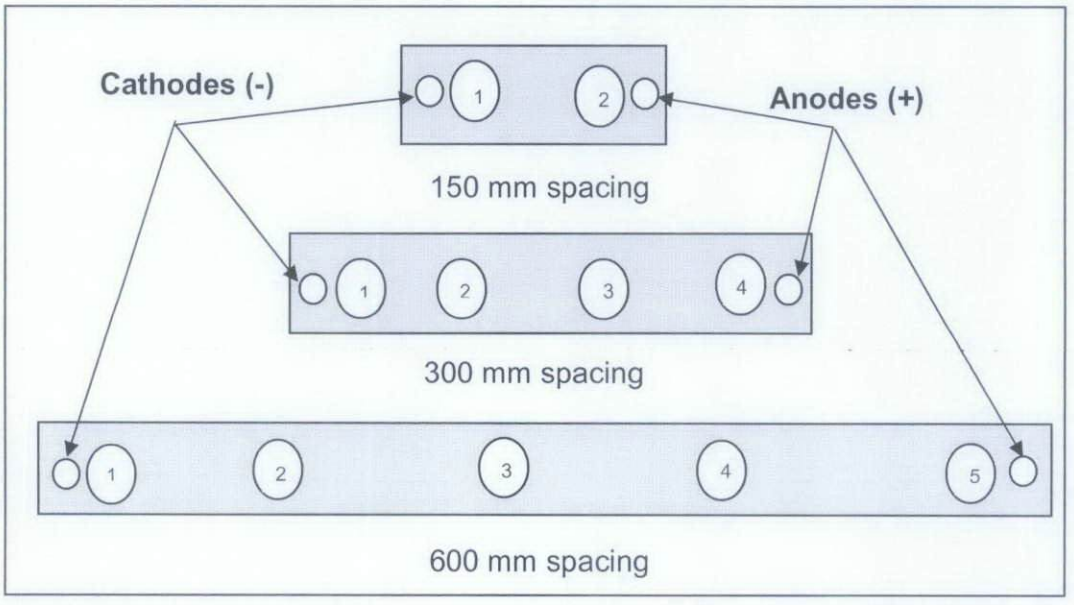


Figure 3.21 Position of electrodes and locations of extruded samples

- The small electrochemical box were divided into two compartments where the 300 mm spacing was conducted in one side of the compartment and the 150 mm spacing test in the other side .
- The positions of electrodes and locations where samples were extruded are shown in Figure 3.21.
- Chemical or distilled water were induced into the system by using the mechanism as shown in Figure 3.18.
- Voltages at different points along the sample were recorded at different intervals of time during treatment as given in Table 3.15.

Table 3.15 Distance from anode and interval of time for voltage readings

150mm spacing	Distance from anode (mm)	10	38	75	112	140	-	-	-	-
	Time interval (hr)	0	3	24	96	168	-	-	-	-
300mm spacing	Distance from anode (mm)	10	75	150	225	290	-	-	-	-
	Time interval (hr)	0	3	24	48	96	172	-	-	-
600mm spacing	Distance from anode (mm)	10	75	150	225	300	375	450	525	590
	Time interval (hr)	0	3	24	48	96	144	168	-	-

For the tests using 300 mm spacing, the following additional tests were conducted after treatment.

i. Atterberg limits

ii. pH

iii. conductivity

iv. XRF, XRD, SEM and EDX

Effluent from the soil sample in test using 300 mm spacing was discharged through the discharging tube and collected in a beaker. The following tests were then conducted on the effluent.

i. pH

ii. conductivity

iii. AAS to determine the cation concentration

For the tests using 150 and 600 mm spacings, the following additional tests were carried out after treatment

i. pH

ii. conductivity

3.2.6 Electrochemical tests on slope-200 mm spacing

The summary of the tests is given below;

Table 3.16 Summary of electrochemical tests on slope-200 mm spacing

Test no.	Type of chemical and molarity	Wt. of soil (kg)	Wt. of water (kg)	Wt. of fluid in bottle (kg)	Total moisture content (%)	Voltage (V)	Test period (days)
1	1mol $CaCl_2$	10	4.0	1.0	50	100	7
2	1mol $Ca(NO_3)_2$	10	4.0	1.0	50	100	7
3	Dist. water	10	4.0	1.0	50	100	7

- The angle of the slope was about 30° as shown in Figure 3.17.
- Copper tubings were used as the electrodes.
- The arrangement of electrodes is shown in Figure 3.22.
- The fluid/chemical was induced in the soil by using the same mechanism as shown in Figure 3.18.

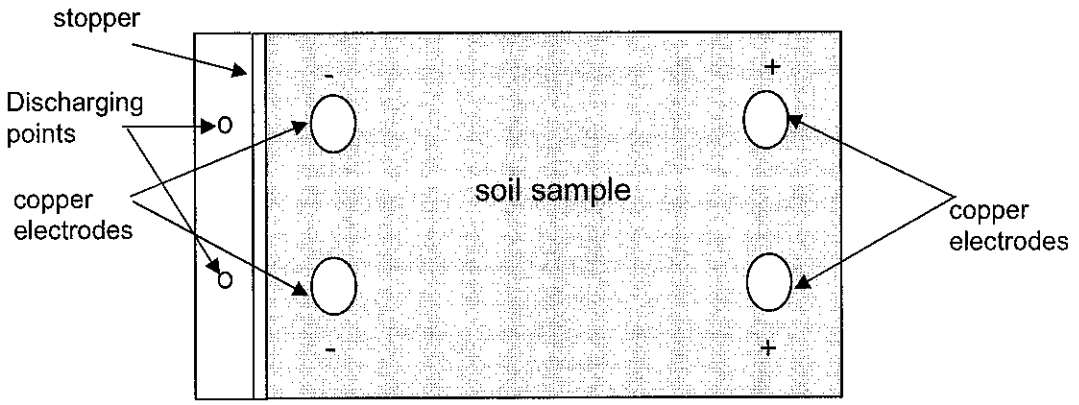


Figure 3.22 Arrangement of electrodes

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 Kaolinite soil properties

Results of the various tests on the basic properties of soil as mentioned in section 3.1 are given in Table 4.1. Supplementary results are included in Appendix A.

Table 4.1 Basic physical and chemical properties of kaolinite soil used in tests

Basic physical and chemical properties of soil	
Natural moisture content (%)	39.9
Liquid limit (%)	35.8
Plastic limit (%)	27.3
Plasticity index (%)	8.5
Specific gravity	2.63
Particle size analysis	
Clay (%)	5.8
Silt (%)	38.6
Sand (%)	53.6
Vane shear strength (kPa)	19.35
Hydraulic conductivity, k_h (cms^{-1})	3.1×10^{-5}
Electro. permeability, k_e (cm^2s^{-1}/V)	4.2×10^{-5}
Coef. of consolidation, C_v (m^2/min)	9.86×10^{-5}
Compression index, C_c	0.23
Coef. of vol. compressibility M_v (m^2/kN)	2.56×10^{-4}
pH	5.19
Conductivity (μS)	80
Al_2O_3 (%)	30.7
SiO_2 (%)	61.7

The sample was taken at a site belonging to Associated Kaolin Industries Sdn. Bhd. The picture of the site is given in Figure A1, Appendix A. The kaolin deposits in Tapah-Bidor area was probably originated from the hydrothermal alteration of the metasediments and granite due to intrusion of a granite stock near Tapah. The bedrock underlying the kaolin deposits consists of phyllite, schist, slate and limestone. It was observed that the thickness of the kaolin deposits from samples taken in this Tapah- Bidor area ranges from 0.1 to 13.7 metres, Sulaiman (1991). Particle size analysis from Table 4.1 shows that the sample falls under the sandy silt category according to the British Soil Classification System. Referring to Figures A2a and A2b in Appendix A, XRD tests indicate that the sample contains predominantly kaolinite minerals with appreciable amount of fine quartz and small trace of illite while the breakdown of the chemical compositions is given in Table A1, Appendix A. In its natural state at site, the soil is acidic with an average pH value 5.19 .An undrained shear strength of 19.35 kPa obtained from vane shear test falls within the range of 12.5-25.0 kPa, categorizing the sample as soft soil. The hydraulic conductivity, k_h, was 3.1×10^{-5} cms^{-1} which is lower than 50×10^{-4} cms^{-1}, the maximum value of hydraulic conductivity considered to be suitable and advantageous for electroosmotic treatment, Casagrande (1952). The electroosmotic permeability, k_e value of 4.2×10^{-5} cm^2s^{-1}/V was close to the generally accepted value of 5×10^{-5} cm^2s^{-1}/V suitable for most practical application, Cassagrande (1952). The hydraulic conductivity and electroosmotic permeability resulted in the ratio of $\frac{k_e}{k_h}$ to be 1.36, a relatively small value for electroosmotic treatment. Since the magnitude of the negative pore pressure depends on the ratio of $\frac{k_e}{k_h}$, it is important to study the efficiency of the selected kaolinite soil with respect to its consolidation and dewatering capacity while having such a small ratio of $\frac{k_e}{k_h}$.

4.2 Electroosmotic Tests

4.2.1 Electroosmotic cell test – soil passing 425 μm sieve

This category of experiment consisted of two set of tests; one set was conducted with only copper electrodes and the other one was with various types of electrodes. The same type of electrodes is used for both anode and cathode in each experiment.

4.2.1.1 Tests with only copper electrodes

Table 4.2 shows results for all the experiments conducted for this set of tests. Settlement shows an increasing trend ranging from 11.7 - 16.4 mm for increase value of surcharges for test without applied voltage (non-electroosmotic). For tests with applied voltage (electroosmotic) with 20 kPa surcharge, increasing the voltage also resulted in an increase of settlement/consolidation ranging from 13.1 mm at 10V to 17.5 mm at 200V. However results show that the settlement effect of 100V and 200V with 20 kPa surcharge exceeds the settlement value for 0 V-30kPa test.

Table 4.2 Results for tests in electroosmotic (cell) - soil passing 425 μm sieve

Voltage (V)	0	0	0	10	20	30	100	200
Surcharges (kPa)	10	20	30	20	20	20	20	20
Settlement (mm)	11.7	12.5	16.4	13.1	13.95	14.92	16.9	17.5
Moisture content (%)	36.38	35.82	35.14	36.0	35.6	34.8	33.3	32.59
Reduction of moisture content (%)	13.62	14.18	14.86	14.3 -	14.4	15.2	16.7	17.41
Strength (kPa)	4.7	8.5	15.12	9.1	10.5	11.88	23.78	31.0
Maximum current (mA)	0	0	0	0.91	1.54	1.75	10.83	18.33
Max. current density (mA/cm^2)	0	0	0	0.011	0.019	0.022	0.14	0.23

Figure 4.1 shows much of the settlement for the non-electroosmotic and electroosmotic test (10V-30V) took place within the first 20 minutes. However, for 100 V-20 kPa and 200 V-20 kPa tests, the period of main settlement extended to about 70 minutes or so. This indicates that a higher initial voltage and hence a higher initial current density induced a higher magnitude of consolidation. By comparing all the experiments having 20 kPa surcharge, it could be seen that the rate of consolidation was about the same for all. The major difference was the variation of the magnitude of consolidation that occurred within the same span of time. This is in agreement with equation 2.18 by Esrig (1968) which indicates that electroosmotic permeability does not influence the rate of consolidation but only influence the magnitude of consolidation.

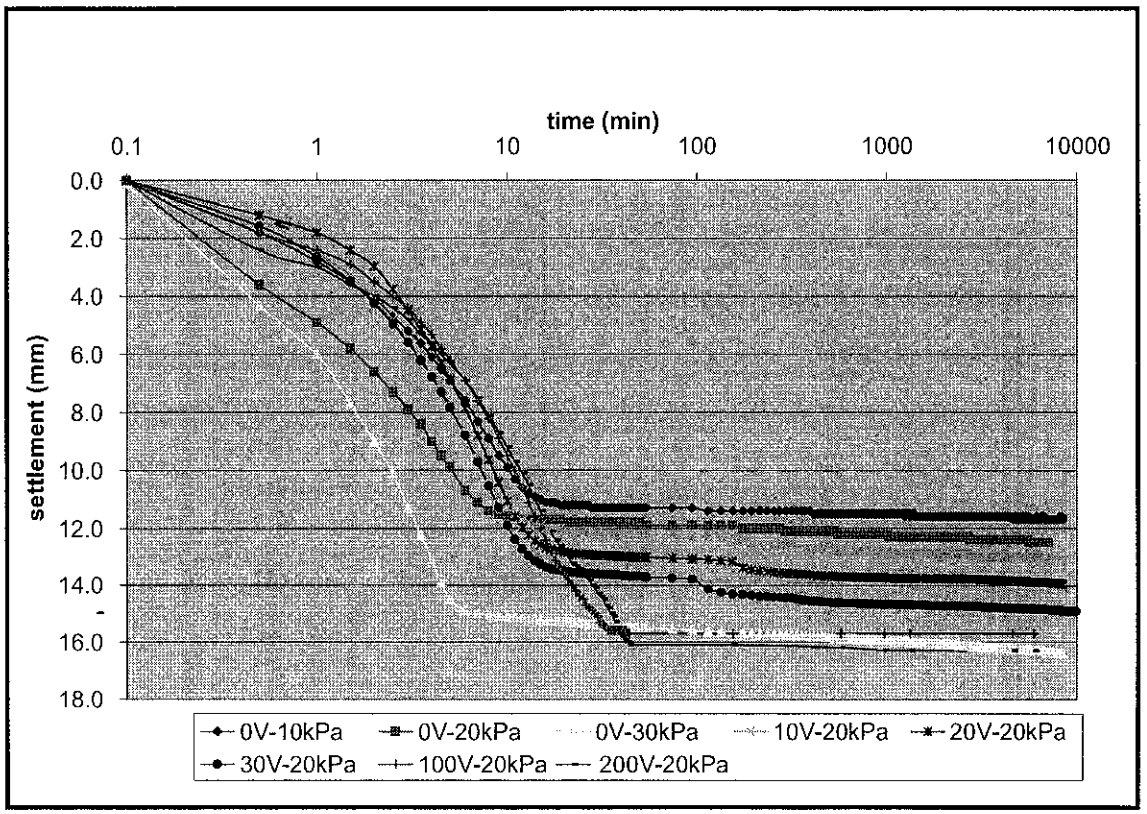


Figure 4.1 Settlement vs. time-electroosmotic cell tests (425 μm)

Beyond the point where the major settlement took place, the rate of settlement and the rate of expulsion of pore water decreased. This phenomenon is in accordance with

findings by Gray and Mitchell (1967) who indicated that electroosmotic efficiency decreases with a decrease in moisture content.

The effectiveness of using electroosmotic treatment in the test could also be attributed to the fact that the value of hydraulic conductivity, k_h for the raw sample was about 3.1×10^{-5} cms^{-1} where as mentioned earlier, a soil having k_h value of 50×10^{-4} cms^{-1} or more will have no advantage of using electroosmotic treatment.

By referring to Figure 4.2, it is observed that the results for the moisture content conformed with the magnitude of consolidation. With just an applied voltage of 10V with 20 kPa surcharge, the moisture content reduction achieved was more than the moisture content reduction for the same 0V-20 kPa test. The lowest moisture content was achieved in the 200V-20 kPa test with a moisture content value of 32.59% which was about 22.7% reduction from the 0V-20 kPa test. A higher decrease in moisture content would generally indicate a higher consolidation and strength gain in electrosmotic treatment.

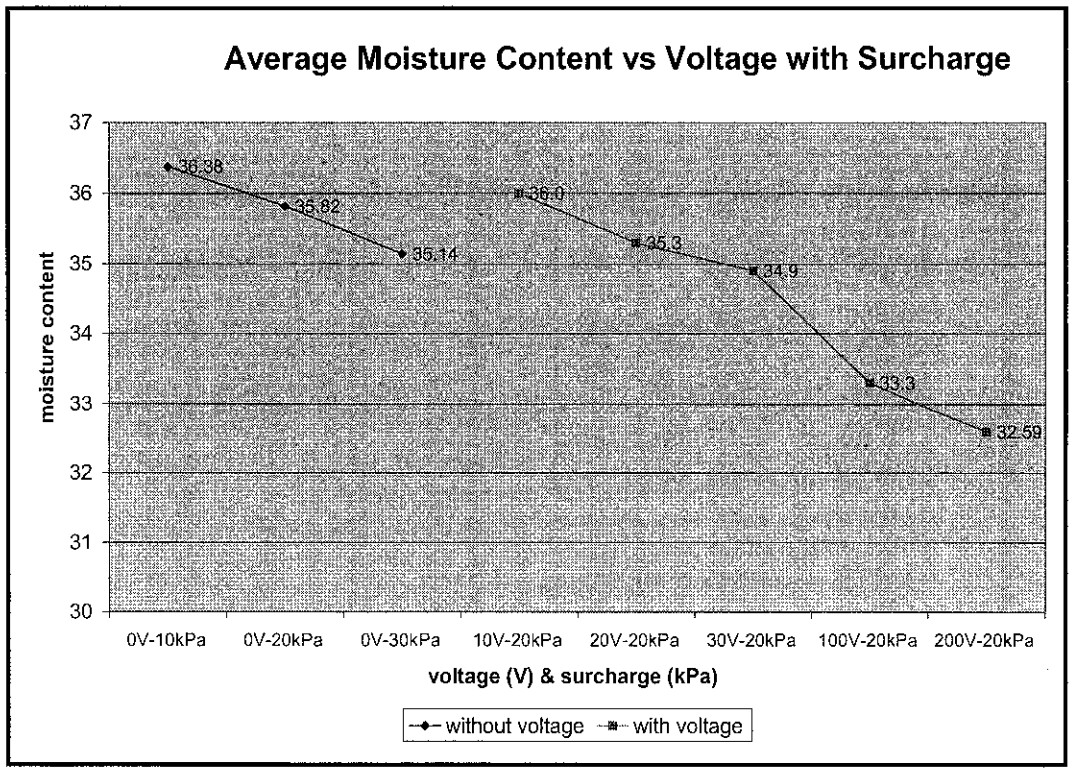


Figure 4.2 Average moisture content vs. voltage with/without surcharge-electroosmotic cell tests (425 μm) – (not to scale)

As the boundary conditions for this series of experiments were close anode, open cathode, theoretically the negative pore pressure development should be represented by equation 2.14. Although pore pressure measurement was not taken during the test, results from the magnitude of consolidation shows that theoretically a higher negative pore pressure was generated at the anode and hence a bigger magnitude of consolidation was achieved for a higher voltage test. Also, a higher reduction of moisture content as obtained in the higher voltage tests would also indicate a higher increase in the negative pore pressure.

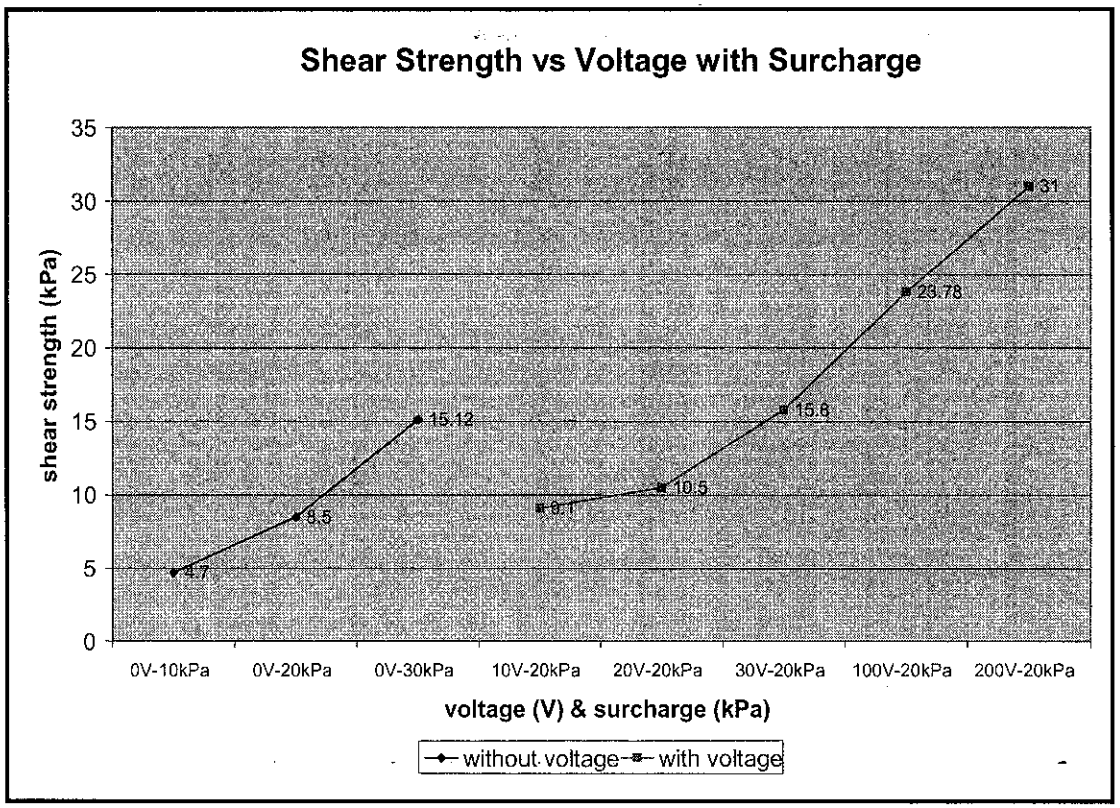


Figure 4.3 Shear strength vs voltage with/without surcharge-electroosmotic cell tests (425 μm) – (not to scale)

Figure 4.3 shows the value of shear strength for both the non-electroosmotic and electroosmotic test. Again, treatment using 100V-20 kPa and 200V-20 kPa surpassed the value of shear strength achieved for 0V-30 kPa test; the highest being 31.0 kPa generated by the 200V-20 kPa test. Note that by applying a mere 30V using 20 kPa surcharge could exceed the shear strength for the non-electroosmotic 30 kPa test. Comparing all the tests

using 20 kPa shows that the increase in shear strength for 200V-20 kPa test (31.0 kPa) was about 2.6 times more or 260% increase from the 0V-20kPa test (8.5 kPa). The corresponding moisture content for the same tests was 32.59% and 35.82% respectively with a decrease in moisture content of only about 3.23%. Percentage wise, the decrease was only about 10%. It is not surprising that a small decrease in moisture content, 10% in this case, could result in a very high increase in shear strength (260%) due to the fact that from the work of Casagrande (1951), he found that small reduction in moisture content by electroosmosis could produce significant increase in soil strength. Note that in the same series of tests, an increase of 20 kPa surcharge for non-electroosmotic test (from 10 kPa to 30 kPa) resulted in strength increase of 10.42 kPa which was only about 220% increase from 4.7 kPa.

The current variation with time is shown in Figures 4.4 and 4.5. They show a typical characteristic of current variation in the sense that in electroosmotic treatment, current or current density will gradually reduce from the initial maximum value.

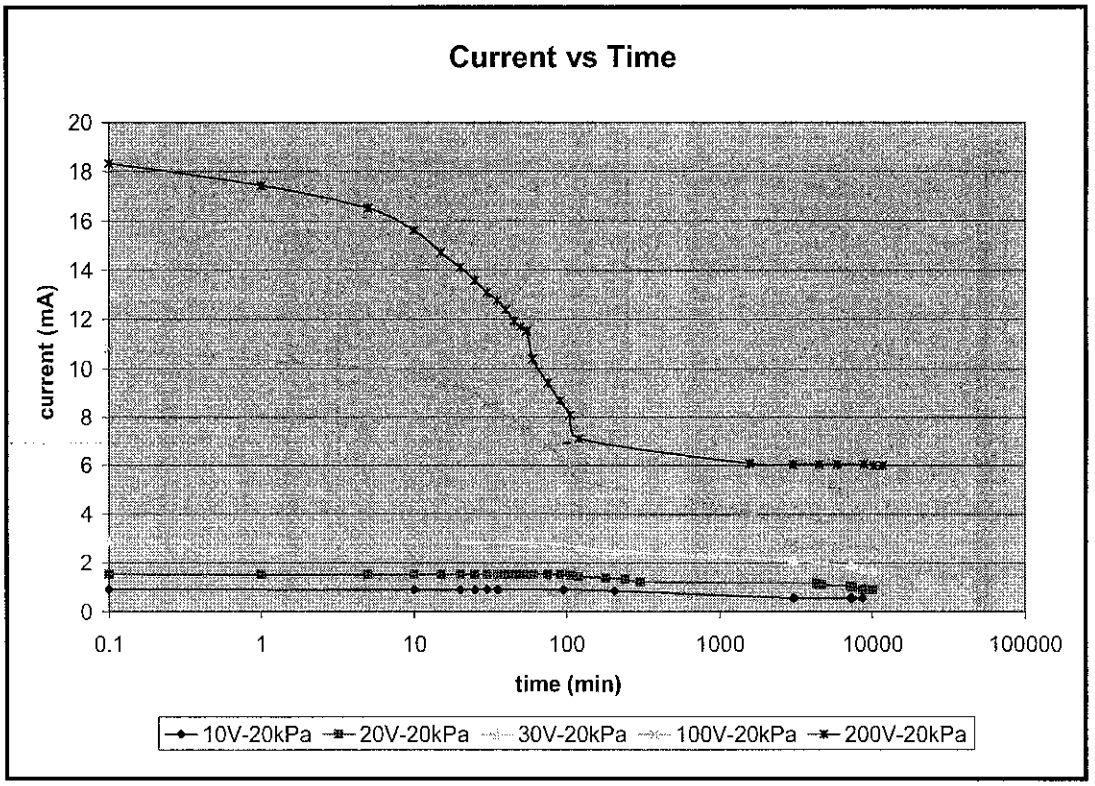


Figure 4.4 Variation of current with time-electroosmotic cell tests (425 μm)

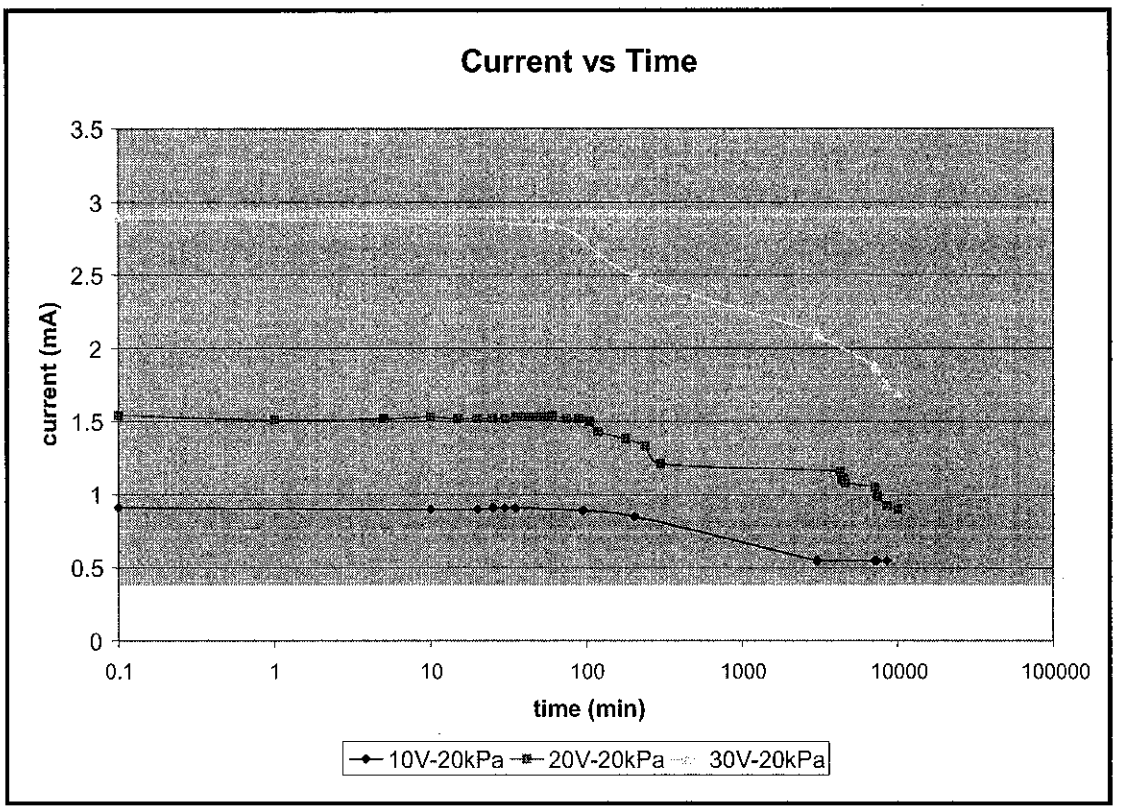


Figure 4.5 Variation of current with time-electroosmotic cell tests (425 μm)

The reduction of current shown in Figures 4.4 and 4.5 indicates the concurrent decrease in pore water. A clear reduction in the magnitude of current could be seen from the plots for 100V-20 kPa and 200V-20 kPa tests having a reduction of about 7.83 mA and 12.33 mA, respectively, as oppose to the current magnitude for tests using 10V, 20V and 30V. It is interesting to note here that the period of major reduction in the magnitude of current for 100V and 200V tests seems to tally with the period of major settlement for the same tests as shown in Figure 4.1. Both figures show major reduction in magnitude of current and magnitude of consolidation within a period of approximately 0-100 minutes. As the electroosmotic process continued, pore water was reduced and caused a decrease in the conductivity or increase in resistivity of the soil-water system reducing the magnitude of current. Overall results showed that this initial set of tests indicated that electroosmotic effect on the kaolinite soil was relatively significant although the ratio of $\frac{k_e}{k_h}$ was 1.35.

4.2.1.2 Tests using different types of electrodes

Tables 4.3 and 4.4 give the overall results for cell tests using different electrodes.

Table 4.3 Results for cell tests using different type of electrodes - soil passing 425μm sieve

Type of Electrode	Brass	Aluminium	Steel	Carbon	Copper
Voltage (V)	30	30	30	30	30
Surcharges (kPa)	20	20	20	20	20
Settlement (mm)	12.86	14.9	13.11	15.3	14.92
Moisture content (%)	36.51	35.28	35.44	34.83	34.90
Strength (kPa)	11.4	14.78	15.2	16.3	15.8
Maximum current (mA)	2.54	2.6	2.84	3.08	2.89

Table 4.4 Results for cell tests comparing carbon and copper electrodes - soil passing 425 μm sieve

Type of Electrodes	Carbon			Copper		
Voltage (V)	30	100	200	30	100	200
Surcharges (kPa)	20	20	20	20	20	20
Settlement (mm)	15.3	16.7	16.9	14.92	16.9	17.5
Moisture content (%)	-	-	-	34.9	33.3	32.59
Strength (kPa)	-	-	-	15.8	23.78	31.0
Maximun current (mA)	-	-	-	2.89	10.83	18.33

Figures 4.6 and 4.7 show the settlement behaviour for all types of materials used as electrodes. Brass gave the smallest settlement which was 12.86 mm and the highest was achieved with carbon electrode which was about 15.3 mm. The settlement of soil using copper electrode was not far off from that of aluminium electrode with settlements of 14.92 mm and 14.9 mm, respectively. The highest settlement achieved with carbon electrodes conformed with results from electroosmotic experiments using carbon and copper electrodes on soft Bangkok Clay by Bergado et al. (2003) who observed the same trend of higher magnitude of settlement for the carbon electrodes.

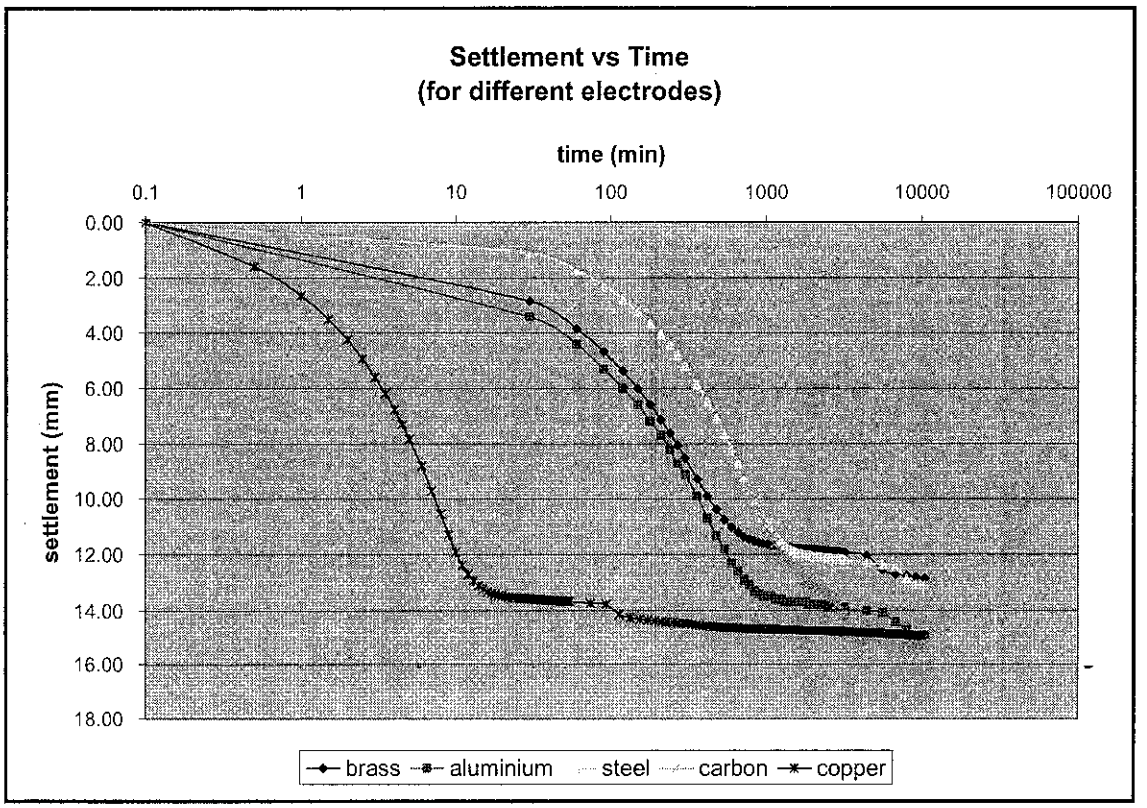


Figure 4.6 Settlement vs. time for different types of electrodes using 30V only-electroosmotic cell tests (425 µm)

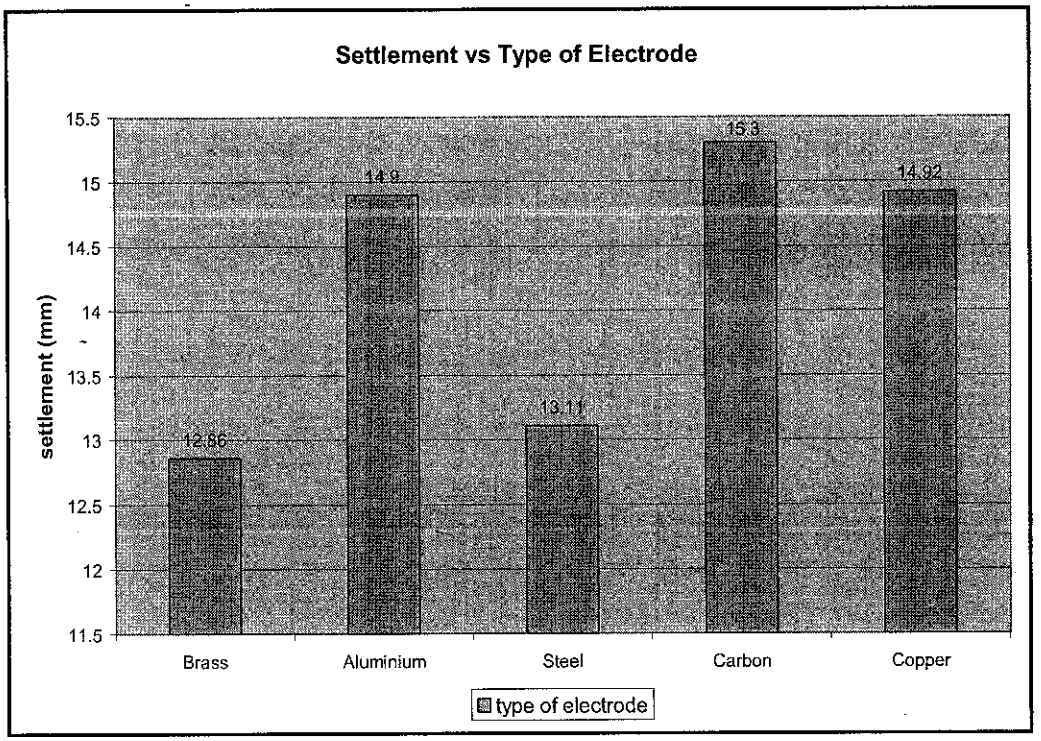


Figure 4.7 Settlement vs. type of electrodes-electroomotic cell tests (425 μm)

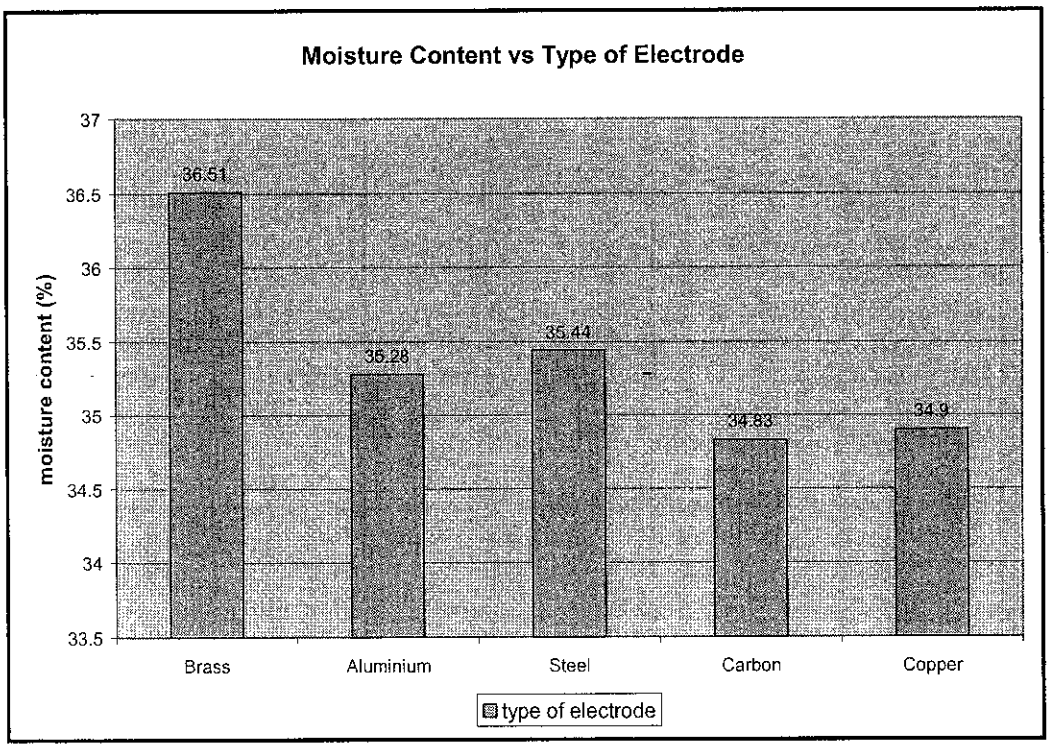


Figure 4.8 Moisture cont. vs. type of electrodes-electroosmotic cell test (425 μm)

Referring to Figure 4.8, the moisture content reduction for copper comes second after carbon with a final moisture content of 34.9% and 34.83% respectively. The same trend was observed in Figure 4.9 where the shear strength for carbon was 16.3 kPa and copper was 15.8 kPa while brass electrode had the lowest value of 11.4 kPa. The current variation with time is shown in Figure 4.10. It was observed that during the tests when 30V was used at least some bubble formations were seen at the internal surface of the cell wall for all the different type of electrodes. This was probably due to the formation of hydrogen (H_2) gas at the cathode which actually traveled upwards and diffused into the soil and out through the opening on the top side (anode side) of the electroosmotic cell. No clear indication of gas formation at anode was seen. Also the usage of 10V, 20V and 30V resulted in no major traces of oxides formation at anode for all types of electrodes except for a little trace of green patches of oxide just beneath the copper anode due to corrosion when applying 30V.

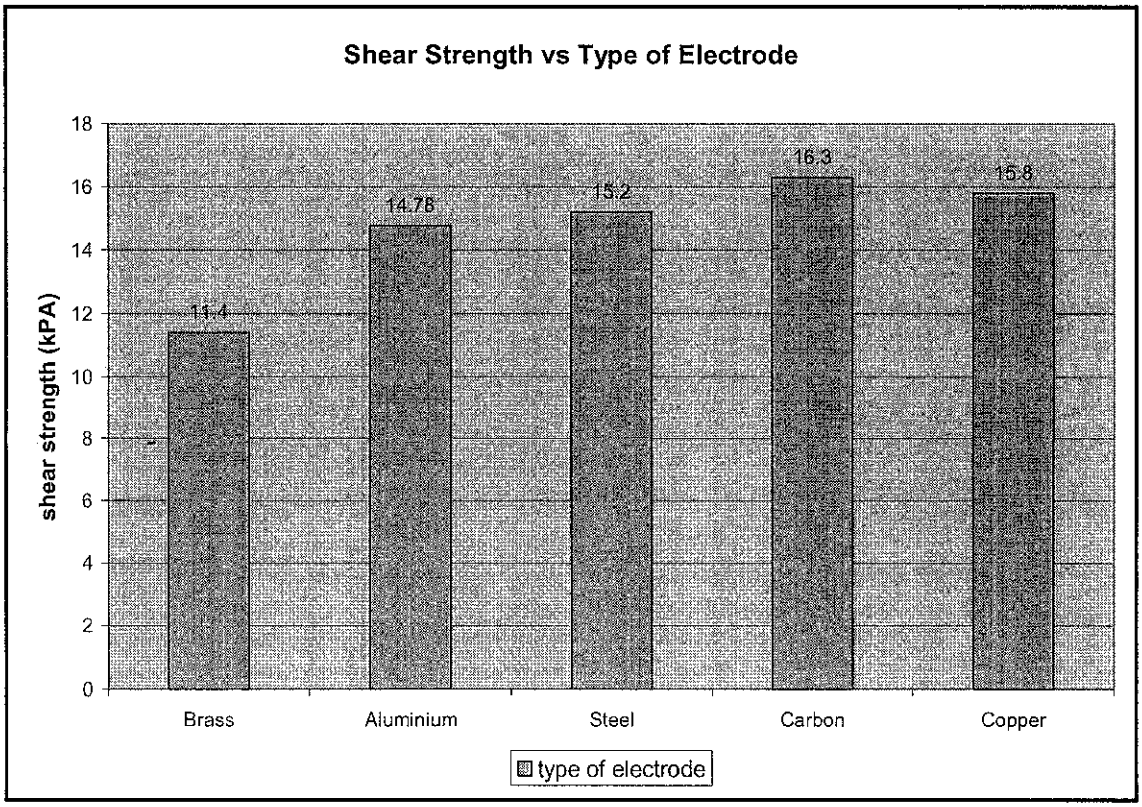


Figure 4.9 Shear strength vs. type of electrodes-electroosmotic cell test (425 μm)

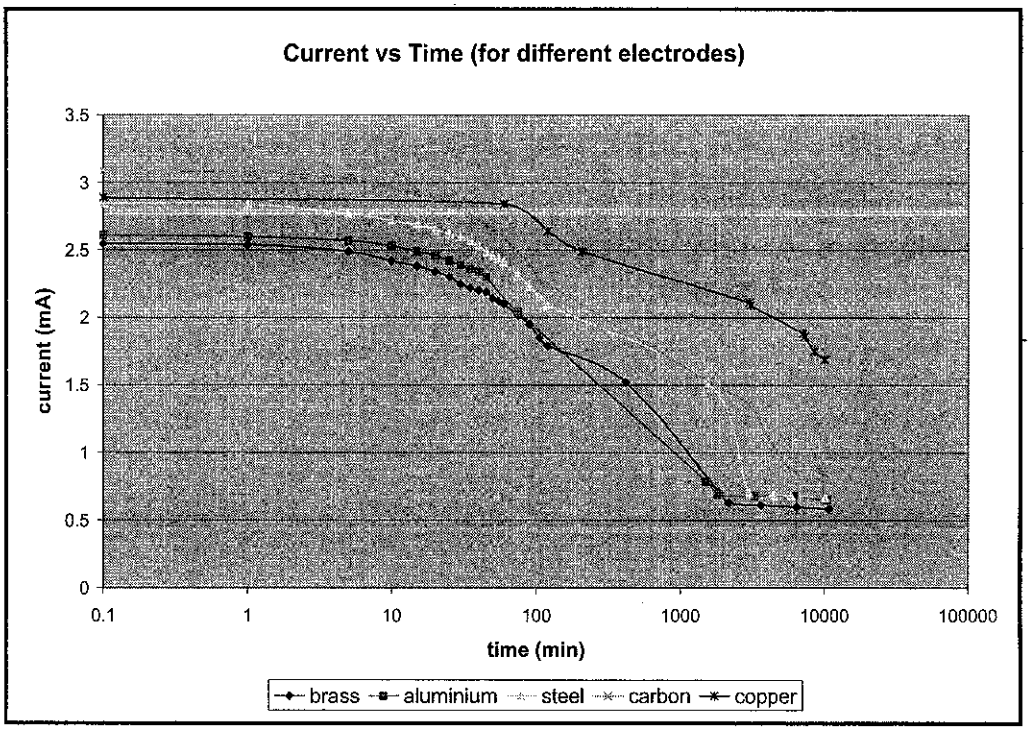


Figure 4.10 Variation of current with time for different electrodes-electroomotic cell tests (425μm)

The observation is in concurrence with the findings of previous researchers. They observed that when copper is used at the anode, copper oxide is formed at the anode with little or no liberation of oxygen. Hamir (1997) also validated this finding when he used different types of electrodes in part of his research on electroosmotic treatment on silty clay. The performance of steel in the aspects of settlement and reduction of moisture content were less than that of aluminium in this experiment and this seems to contradict to the observations made by Sprute and Kelsh, (1980) and Lockhart, (1983) where in field applications steel and carbon are more effective than aluminium, lead and carbon black. Another seemingly contradicting factor observed in this test is the shear strength achieved by using aluminium electrodes was less than that of steel whereby Adamson et al., (1965) pointed out that aluminium anodes provide Al^{3+} ions for base exchange and cementation leading to a irreversible process better than the effect of steel electrodes. However, the author believes that this effect of Al^{3+} ions is generally applicable in electrochemical treatment of soil where chemical are injected in soil for the purpose of

stabilization and is not much effective in the normal electroosmotic process in a soil-water system.

The results for settlement (Figure 4.11), moisture content and strength for carbon and copper were close. This shows the effectiveness of both electrodes in electroosmotic process, therefore further tests using 100V and 200V were carried out for both. Referring to Figure 4.10, it was found that when 100V and 200V were used, the magnitude of settlement for copper exceeded that of carbon. Previously when 30V was applied, the magnitude of settlement for carbon electrode exceeded that of copper by 0.02 mm. Note that the increase in the magnitude of settlement from 100V to 200V were small for both and much more smaller in the case of carbon electrode. Comparing with the condition at anodes for both carbon and copper electrodes, the usage of high voltages and especially 200V showed a clear green traces of formation of copper oxides at the anode for copper electrode while no clear trace of any form of oxides were formed at carbon anode.

In conclusion, from the five types of materials used for electrodes, copper electrodes produced good results in terms of shear strength increase and reduction in moisture content second only to carbon. However, for actual usage, carbon electrodes are probably not practicle due to its high cost.

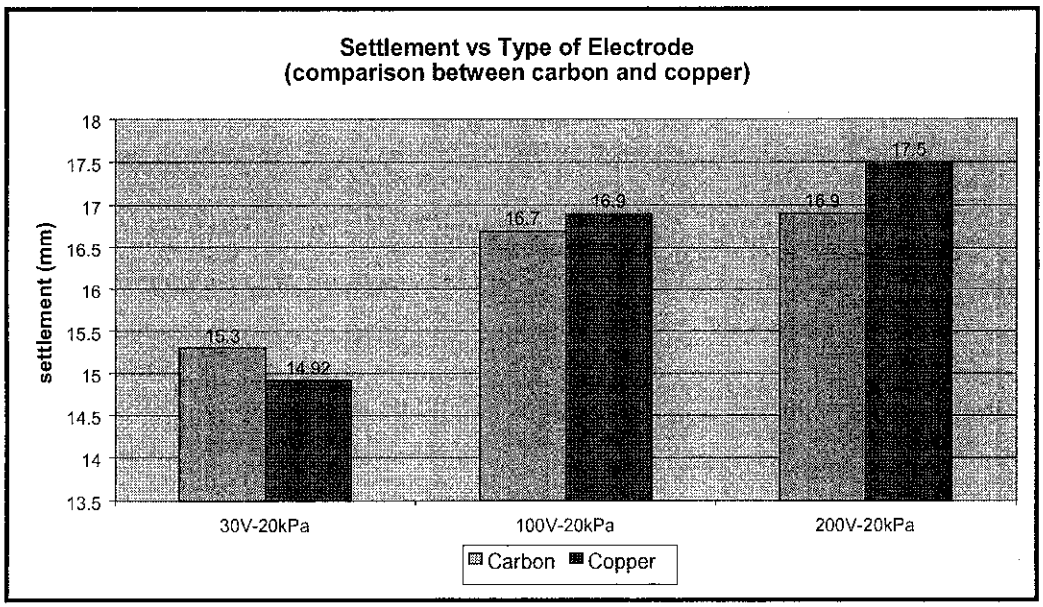


Figure 4.11 Comparison of settlement between carbon and copper electrodes

4.2.2 Electroosmotic box tests - soil passing 425 μm sieve

This category of experiment also consisted of two set of tests. One set was conducted with electrode arrangement Type A and the other was with electrode arrangement Type B.

4.2.2.1 Tests using electrode arrangement Type A

As previously mentioned in section 3.2, the box test simulates field condition better than the cell test. The small electroosmotic cell test was a quicker and simpler method of testing as it uses less amount of soil, less loading and took lesser time for sample preparation and experimental set up. The electroosmotic cell test however gave a preliminary result at the behavior and characteristic of electroosmotic treatment of soil. Comparison will then be made with the electroosmotic box test and theoretically the same trend of behavior and changes of the various parameters should prevail.

Table 4.5 shows the overall results for the electroosmotic box test. By referring also to Figures 4.12, 4.13 and 4.14, it could be seen that the settlement behaviour for the box test was the same as what was achieved in the electroosmotic cell tests. All the values having the same 5 kPa surcharge from 0V to 200V show an increasing trend of settlement and shear strength and a decreasing value of moisture content. By comparing the various values between 0V-5.0kPa and 200V-5.0kPa, it is shown that the percentage difference for settlement, moisture content reduction, and strength were 67%, 25%, and 1300% respectively. Comparing with the values obtained from the cell test, the settlement values were not far off from each other's value. The values of final moisture content for the box test were greater for all tests except for the 200V test. The comparison can be seen clearly by referring to Tables 4.2 and 4.5. Likewise, the shear strength achieved was greater for all the tests in the box test. Note that in all the box tests, the surcharge value was approximately one-third than the amount of surcharge applied in the electroosmotic cell test.

Table 4.5 Results for electroosmotic box tests – soil passing 425 um sieve

Voltage (V)	0	0	0	10	20	30	100	200
Surcharges (kPA)	2.5	5	10	5	5	5	5	5
Settlement (mm)	8.59	11.28	16.59	12.7	13.93	15.01	16.47	18.86
Moisture content (%)	40.1	39.02	37.25	38.7	37.91	35.91	34.5	31.06
Reduction of moisture content (%)	9.9	10.98	12.75	11.3	12.09	14.09	15.5	18.94
Strength (kPa)	2.21	4.22	6.06	4.55	5.13	6.29	23.3	59.67
Maximum current (mA)	0	0	0	2.39	5.65	11.2	52.7	71.0
Max. current density (mA/cm^2)	0	0	0	0.02	0.045	0.09	0.42	0.56

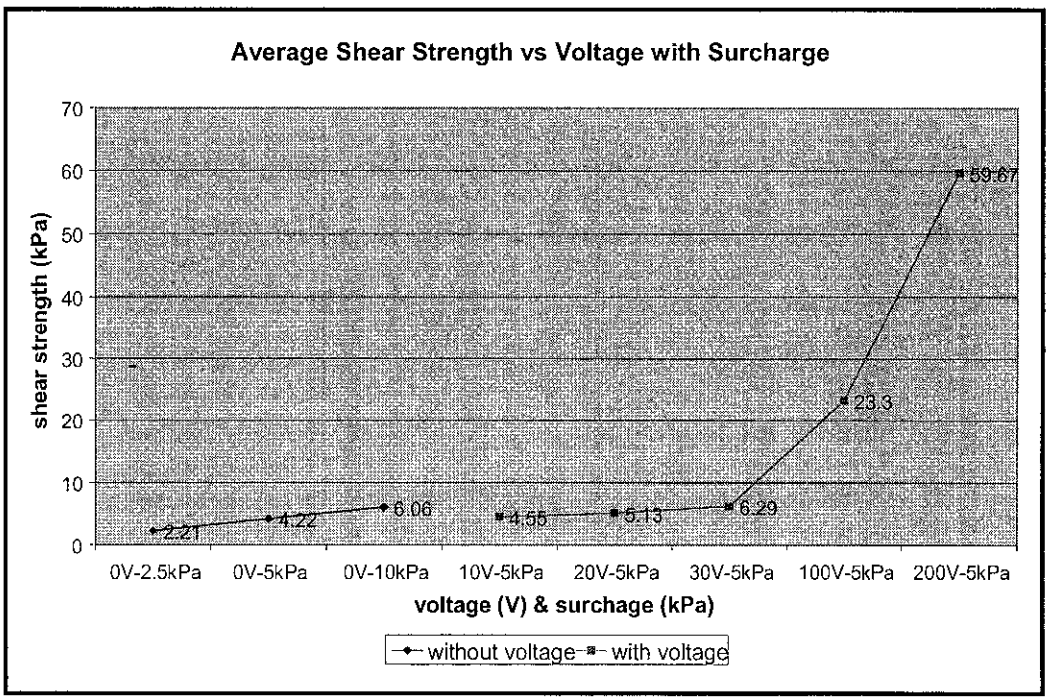


Figure 4.12 Average shear strength vs. voltage with surcharge-electroosmotic box tests (425 μm) – (not to scale)

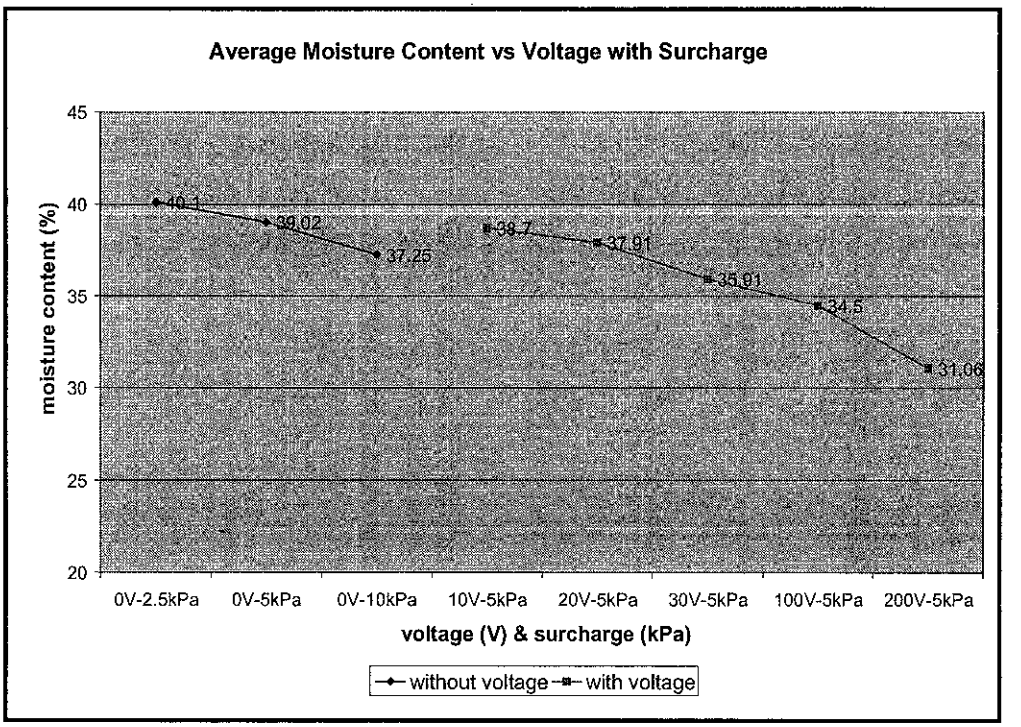


Figure 4.13 Average moisture content vs. voltage with surcharge-electroosmotic box tests (425 μm) – (not to scale)

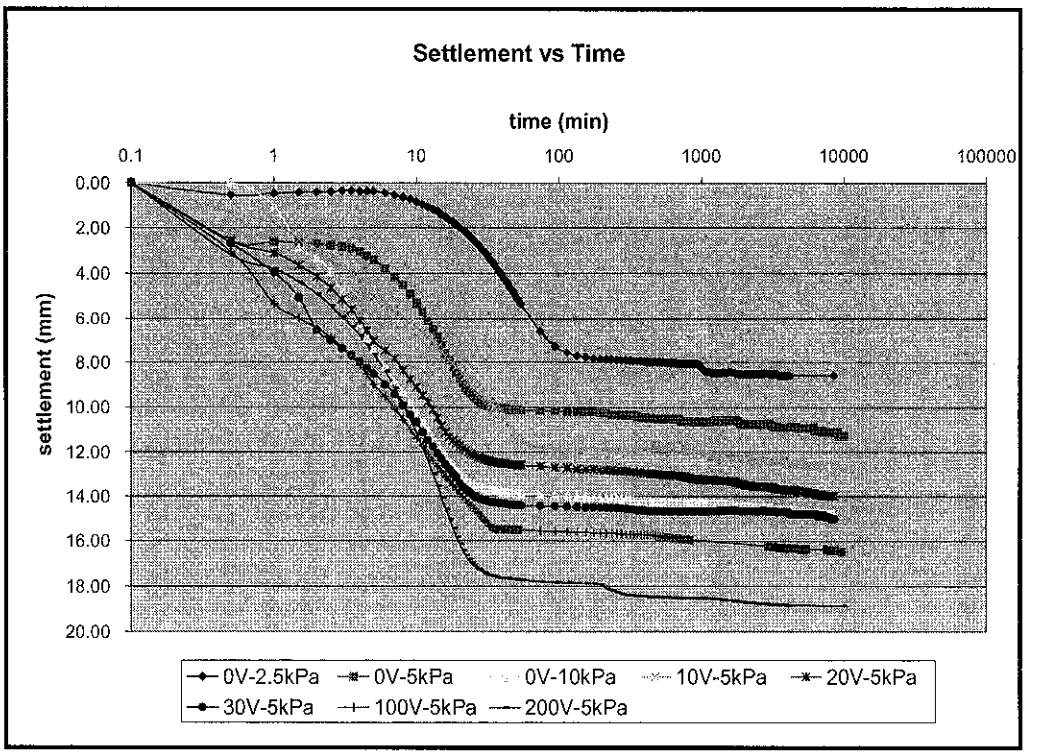


Figure 4.14 Settlement vs. time-electroosmotic box tests (425 μm)

The overall results in settlement, moisture content and strength were about the same for both the electroosmotic box and cell tests. In reality, with less surcharge and the same voltage applied, at least the magnitude of consolidation should be much less in the box tests than what was acquired in the cell test. This could be explained by the fact that although the surcharge was less and voltage applied was the same for both the electroosmotic box and cell test, the decrease in surcharge was offset/compensated by the bigger initial current density obtained for the box tests which was about 2.4 times more than those in the cell tests as shown in Table 4.2 and 4.5. Because the magnitude of settlement/consolidation depends on the consolidation pressure or pore pressure induced which in turn depends on the current density and the soil resistivity as given in equation 2.18, it is obvious here that the bigger current density obtained in box test played a major role in compensating the small surcharge in inducing electrosomotic consolidation. The variations of current with time are shown in Figure 4.15. Note that the application of 100V and 200V in the box tests resulted in a strange effect whereby the current fluctuated repeatedly from high to low especially for the 200V test. The reason as to why the current behaved as such will be explained later in the electrochemical series of tests.

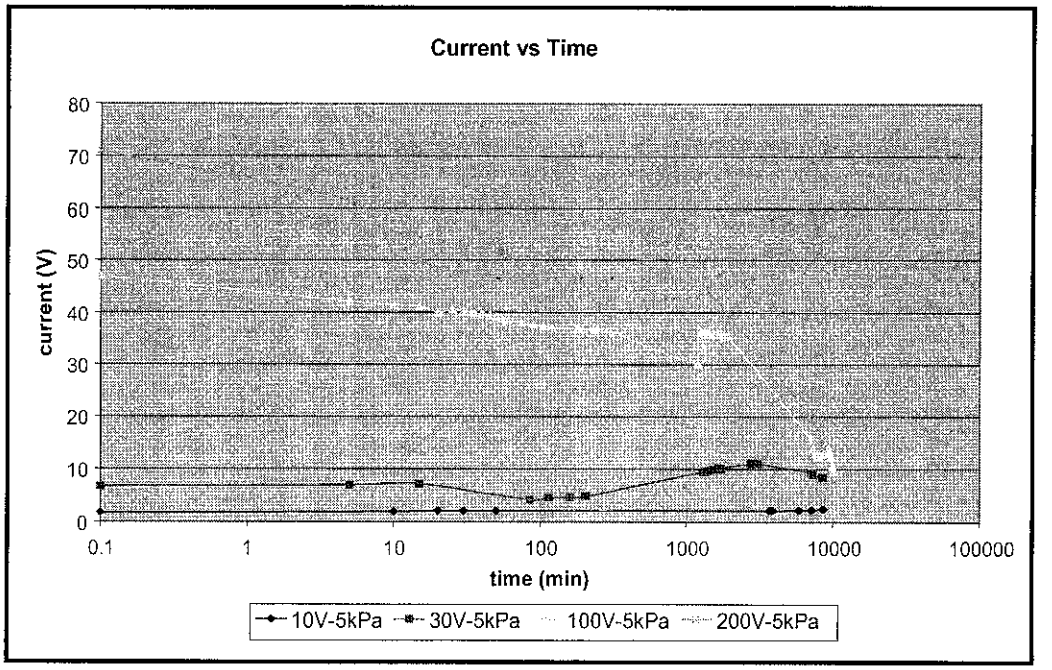


Figure 4.15 Variation of current with time-electroosmotic box tests (425 μm)

4.2.2.2 Tests using electrode arrangement Type B

Table 4.6 shows various results for the two types of electrode arrangements. No clear improvement of values was obtained in arrangement Type B. On the contrary, all settlement, moisture contents and shear strength values for 30V, 100V, and 200V for arrangement Type B are less than the values obtained in arrangement Type A. This could be seen clearer by referring to Figure 4.16, 4.17, and 4.18. It is even more surprising to observe from Figure 4.18 that the magnitude of settlement for 200V in arrangement Type B (15.81 mm) was even less than that of 100V in arrangement Type A (16.47 mm). Shear strength results for arrangement A using 200V was almost 100% more than in arrangement Type B using the same voltage while the increase in shear strength for 100V in arrangement Type A was only 25% more when compared to the same test in arrangement Type B. As far as the initial current value is concerned, minimal difference was observed.

Table 4.6 Results for tests in electrode arrangements Type A and Type B-box tests

Type Of Arrangment	A			B		
Voltage (V)	30	100	200	30	100	200
Surcharges (kPa)	5	5	5	5	5	5
Settlement (mm)	15.01	16.47	18.86	11.58	13.5	15.81
Moisture content (%)	35.91	34.5	31.06	37.89	36.5	34.99
Strength (kPa)	6.29	23.3	59.67	4.43	18.89	29.14
Maximun current (mA)	11.2	52.7	71.0	-	46.9	69.0

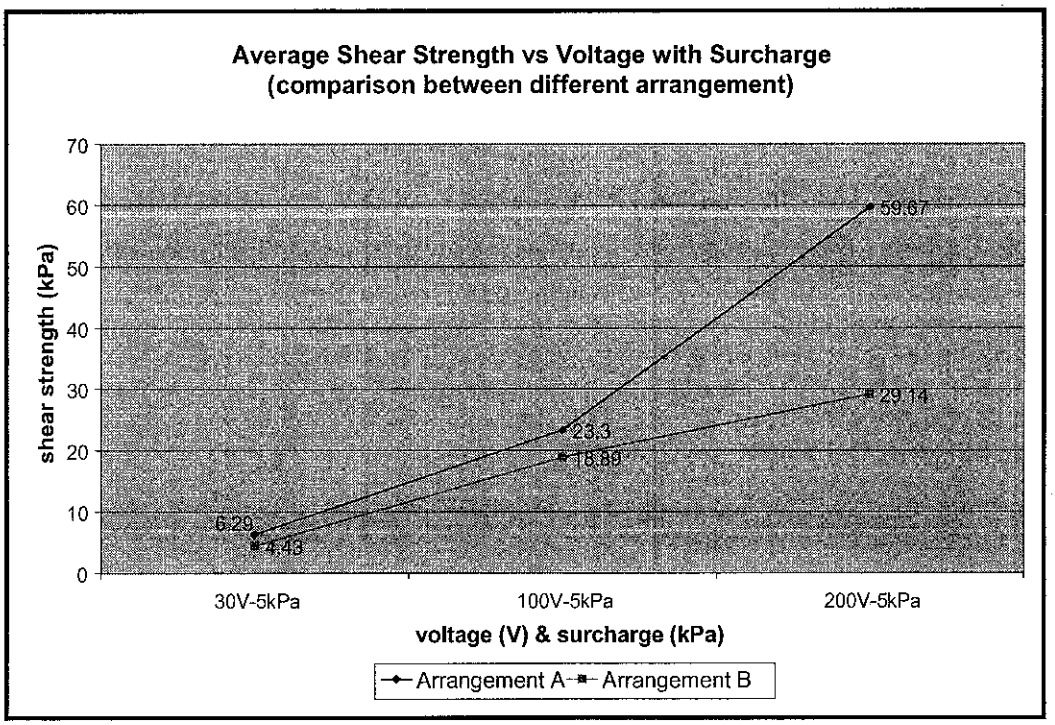
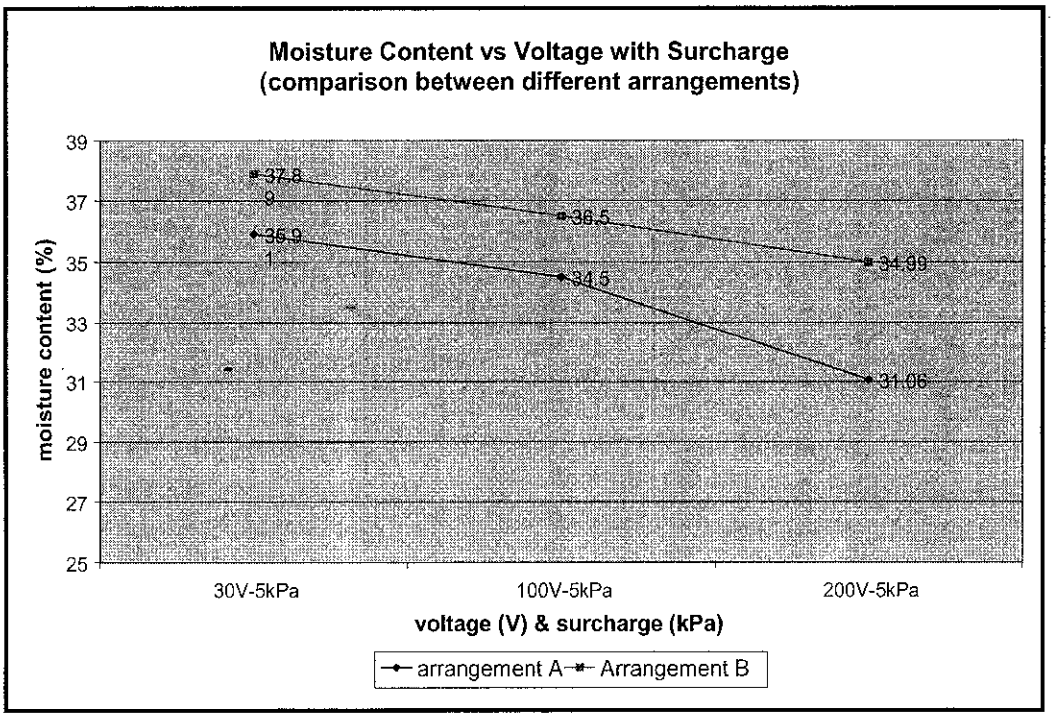


Figure 4.16 Average shear strength vs. voltage with surcharge-electroosmotic box test (425 μm) – (not to scale)



Moisture content vs. voltage with surcharge-electroosmotic box tests (425 μm) – (not to scale)

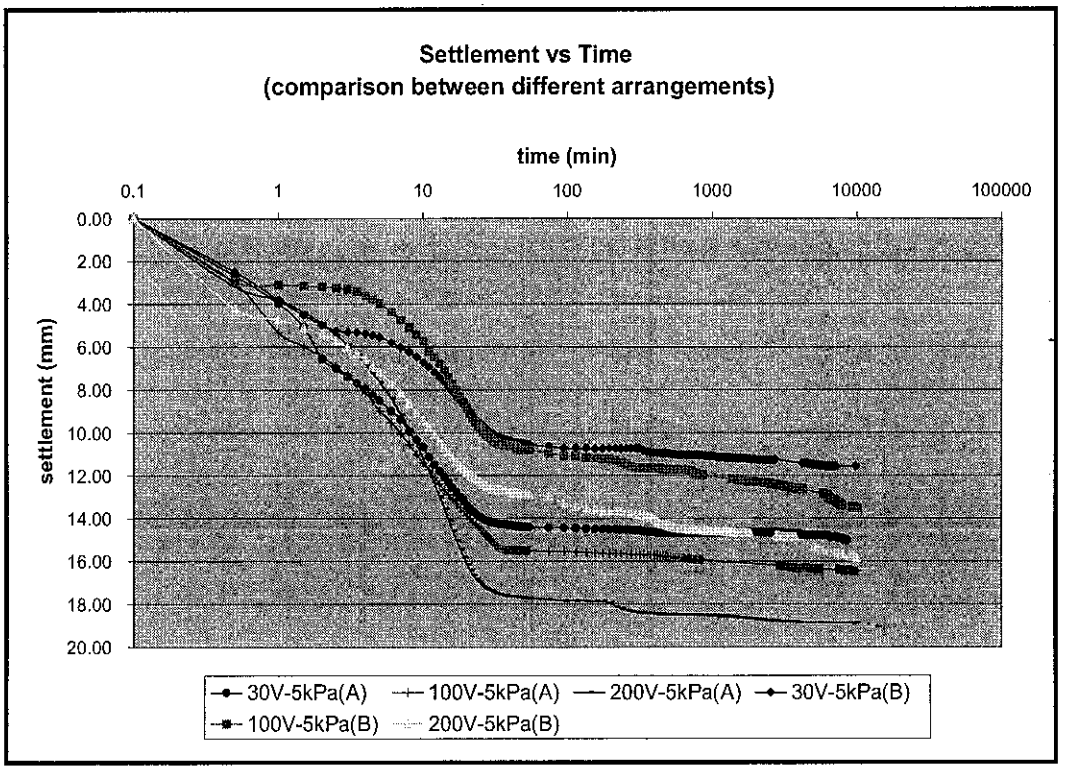


Figure 4.18 Settlement vs. time-electroosmotic box tests (425 μm)

Overall, the effectiveness of arrangement Type B in electroosmotic process was not as effective as in arrangement Type A. This was probably due to the fact that longer paths were taken for water to travel to the discharge point in the center and also there was only one discharge point in the center provided in arrangement Type B and hence causing a slower discharging capacity of the pore water.

4.2.3 Electroosmotic cell tests – soil passing 2mm sieve

Another set of experiments were conducted to look into the aspect of bigger particles size. Experiments on soil particles passing 2 mm sieve size were conducted using similar voltages and surcharges in the previous experiments on soil passing 425 μm sieve. Table 4.7 shows the overall results obtained for this set of experiments.

Table 4.7 Results for electroosmotic cell tests -soil passing 2 mm sieve

	Surcharge and Voltage Conditions					
Voltage (V)	0	0	0	10	20	30
Surcharges (kPa)	10	20	30	20	20	20
Settlement (mm)	12.95	23.58	28.66	26.35	28.08	30.21
Moisture content (%)	46.94	42.64	41.85	42.31	27.74	21.74
Reduction of moisture content (%)	18.06	22.36	23.15	22.68	37.26	43.26
Strength (kPa)	3.61	6.53	7.46	3.72	11.9	14.45
Maximum current (mA)	0	0	0	0.9	1.41	2.05

Figure 4.19 shows the settlement results for all the tests with the one using 30V-20kPa having the highest settlement of 30.21 mm and 0V-10kPa having the smallest settlement of 12.95. Comparing all the tests using 20kPa surcharge, the percentage difference for tests 30V-20kPa and 0V-20kPa was only 28%. Meanwhile, the corresponding percentage difference for reduction of average moisture content (Figure 4.20) and shear strength (Figure 4.21) between 30V-20kPa and 0V-20kPa were 93% and 121% respectively.

From Figure 4.20, it could be seen that the reduction of moisture content from the original value of 65% for 20V-20kPa and 30V-20kPa were 37.26% and 43.26% respectively while the range of reduction of moisture content for the remaining tests were between 18.06% to 23.15%. The seemingly large reduction in average moisture content for 20V-20kPa and 30V-20kPa suggests that the result obtained could either be wrongly taken or could be due to a major discrepancy in the tests conducted.

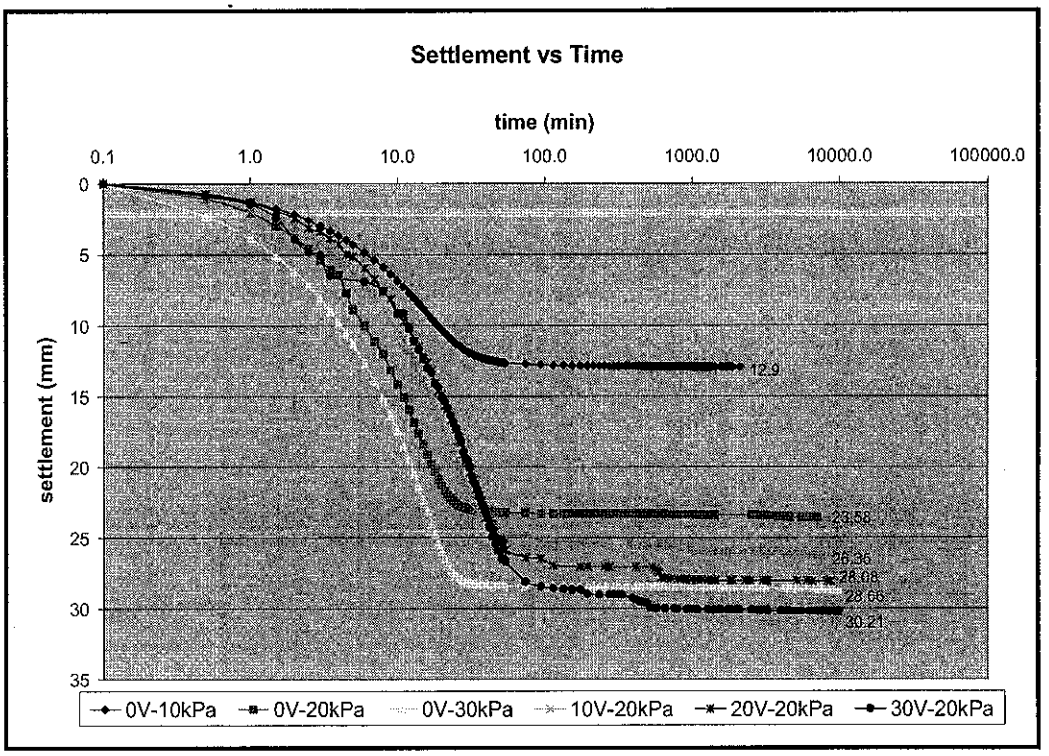


Figure 4.19 Settlement vs. time-electroosmotic cell tests (2 mm)

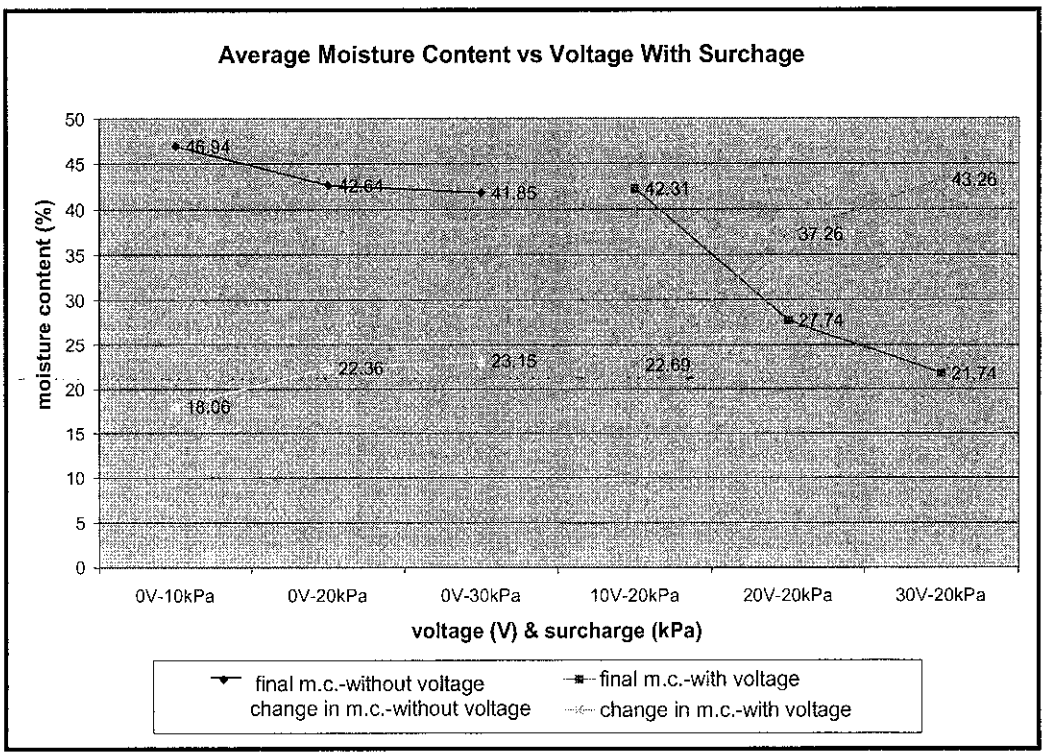


Figure 4.20 Average moisture content vs. voltage- elec.osmotic cell tests (2 mm)

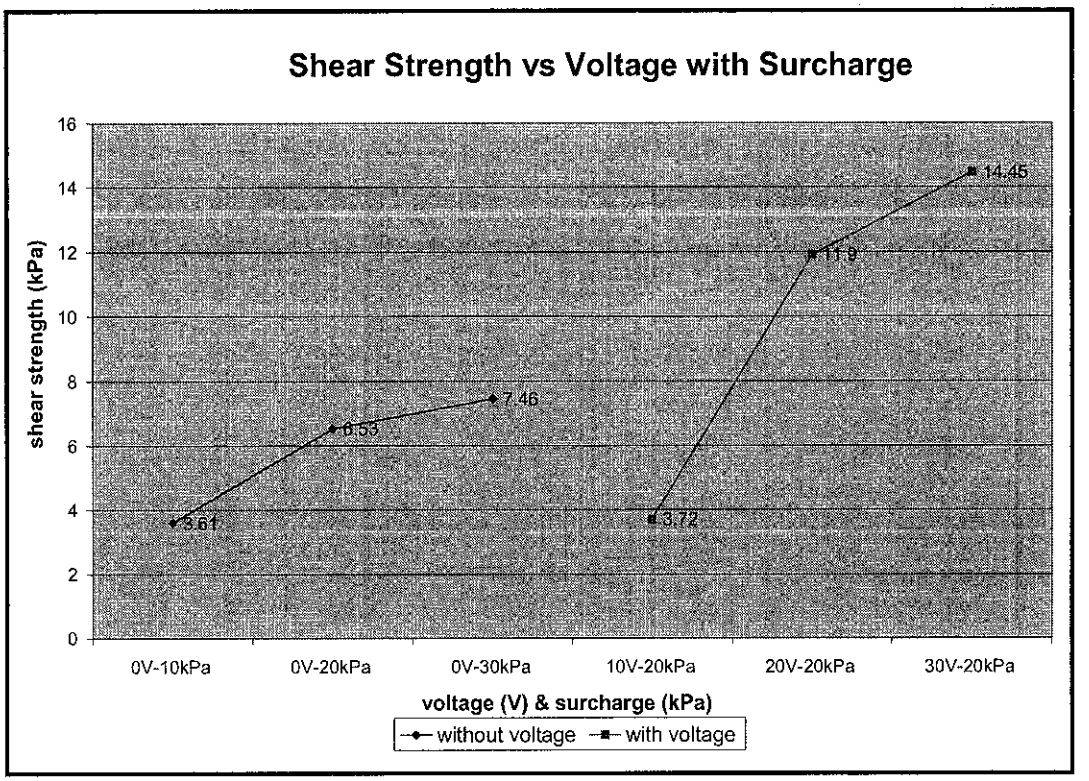


Figure 4.21 Shear strength vs. voltage with surcharge-electroosmotic cell tests (2 mm)

However repeated tests were done for both the tests and the same approximate results were generated. The samples were then sliced into about 15 cm each to look into the changes of moisture content along the sample starting from anode. Refering to Figure 4.22, results for non-electroosmotic tests shows that the values for moisture content at cathodes were not much less than that of the anodes. Big variations of moisture content along the sample for 10V-20kPa was observed indicated by the sloping curve with the anode having 22.95% and cathode having 60.1% close to the initial moisture content of 65%. Referring to the curve for 20V-20kPa test, the variation was lesser than in the 10V-20kPa test. The 30V-20kPa plot was almost vertical indicating an almost uniform moisture content throughout the sample. For the electroosmotic test (10V, 20V, 30V), it was noted that the values of moisture content at anodes were significantly less than that at cathodes especially for 10V and 20V.

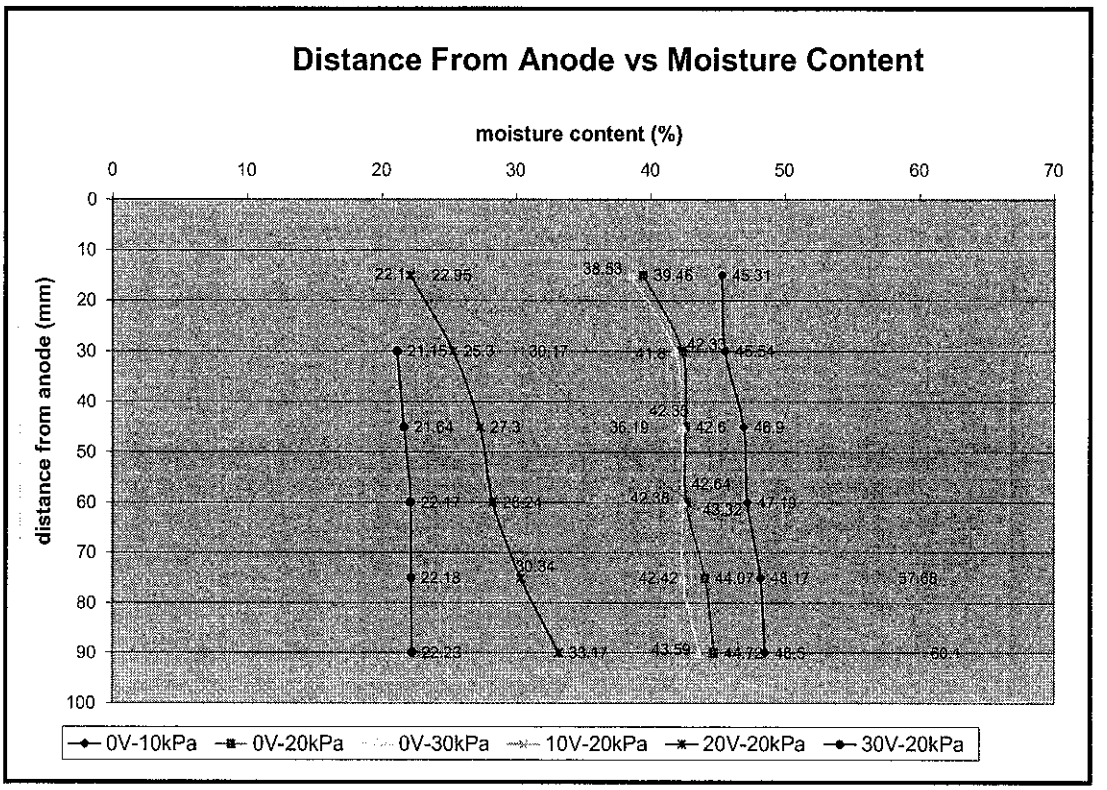


Figure 4.22 Variations of moisture content along the sample-electroosmotic cell tests (2 mm)

The plot for the electroosmotic tests could be related with equation 2.14 whereby the amount of moisture content at a certain point along the sample corresponds with the magnitude of pore water pressure which varies with the voltage at that point. The shape of the curve for 30V-20kPa was almost similar to those without applied voltage with the difference being the big reduction in the moisture content which pinpoints to the efficiency of using 30V and 20V in dewatering process for this kaolinite soil passing 2 mm sieve. This high reduction in moisture content resulted in a significant increase in shear strength in both the tests with value of 14.45 kPa and 11.9 kPa respectively. In fact, the usage of 30V and 20V produced better results in almost all aspects of settlement, moisture content reduction and shear strength gain.

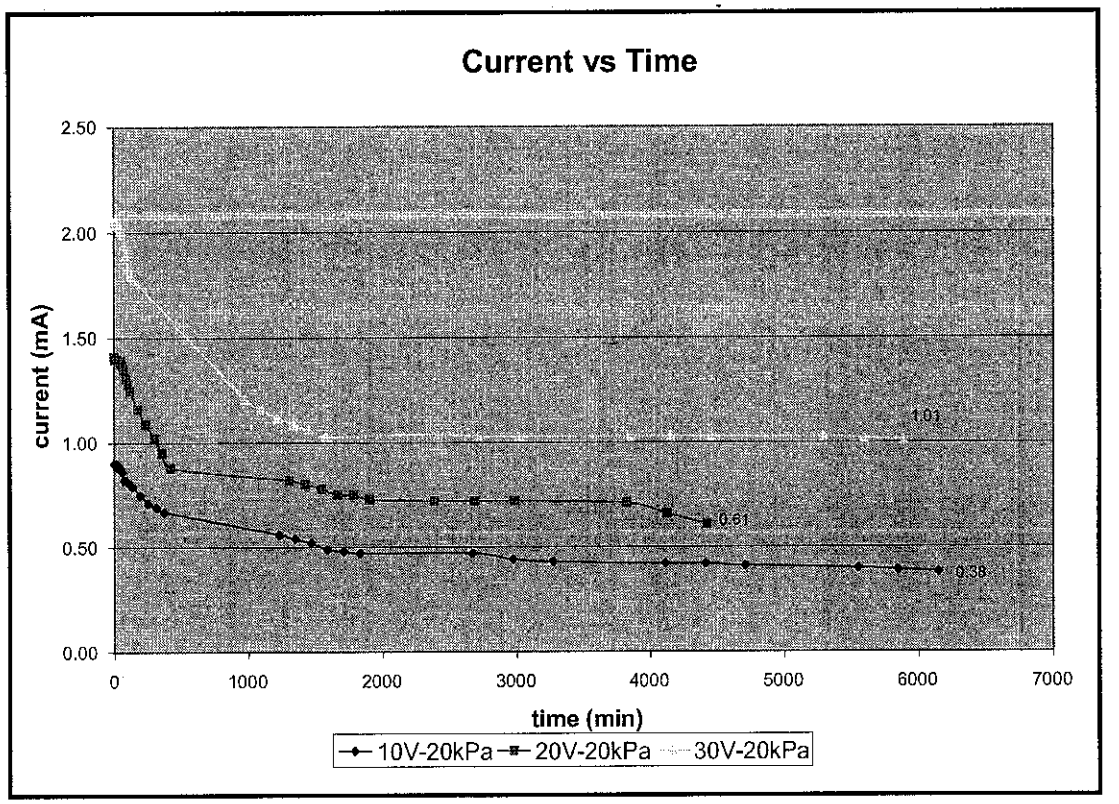


Figure 4.23 Variation of current with time-electroosmotic cell tests (2 mm)

Figure 4.23 shows the current behaviour for tests with applied voltage. All plots seem to show the same trend of reduction in current with the major difference lies in the initial and final magnitude. Comparing to the similar cell tests for soil passing 450 μm sieve, the same overall trend of improvements of increasing surcharge and increasing applied voltage was obtained. This shows the effectiveness of electroosmotic treatment on this sample of kaolinite soil even for bigger particle sizes which is supposed to have a bigger value of hydraulic conductivity, k_h. Since the value of electroosmotic permeability, k_e should remain the same regardless of particle sizes as shown in Figure 2.4, this resulted in a smaller ratio of $\frac{k_e}{k_h}$ (where for 2 mm soil, $\frac{k_e}{k_h} = 1.35$), which theoretically should results in a smaller consolidation pressure and smaller magnitude of consolidation as indicated in equation 2.18. The higher initial moisture content also proved to be very helpful in the effectiveness of electroosmotic treatment since electroosmotic process works better when the moisture content is more.

4.2.4 Electroosmotic box tests – soil passing 2 mm sieve

Table 4.8 gives the various results obtained in this set of box tests for soil passing 2 mm sieve. Referring to Figure 4.24, the overall shear strength increment for electroosmotic treatment for 10V, 20V, and 30V were relatively small, much like what was observed in the previous box test for soil passing 450 μm sieve shown in Figure 4.12. Comparing to the shear strength gain for 20V and 30V with those in the cell test, all strength gain in the box tests were less. The same were observed for the reduction of moisture content and the magnitude of settlement given in Figures 4.25 and 4.26. The trend of settlement in Figure 4.26 again shows that most of the major settlement occurred within the first 0-70 minutes and almost stabilized towards the end of the test period. Note that in this test, the magnitude of settlement for 0V-10kPa was the highest. Overall, the performance of 0V-10kPa for this box test was better than the 30V-5kPa electroosmotic treatment. Though this was just a laboratory results, 30V-5kPa application in field condition would probably generate the same results if the same type of electrode and electrode spacing are used and the same soil particle sizes prevail at site.

Table 4.8 Results for electroosmotic box tests – soil passing 2 mm sieve

	Surcharges and Voltage Conditions					
Voltage (V)	0	0	0	10	20	30
Surcharges (kPa)	2.5	5.0	10	5.0	5.0	5.0
Settlement (mm)	10.0	12.6	25.3	13.5	16.8	18.5
Moisture content (%)	48.88	47.14	46.28	47.29	46.71	46.39
Reduction in moisture content (%)	16.12	17.82	18.72	17.71	18.29	18.61
Strength (kPa)	1.20	2.22	3.42	2.49	2.77	3.05
Maximum current (mA)	0	0	0	3.16	7.99	11.8

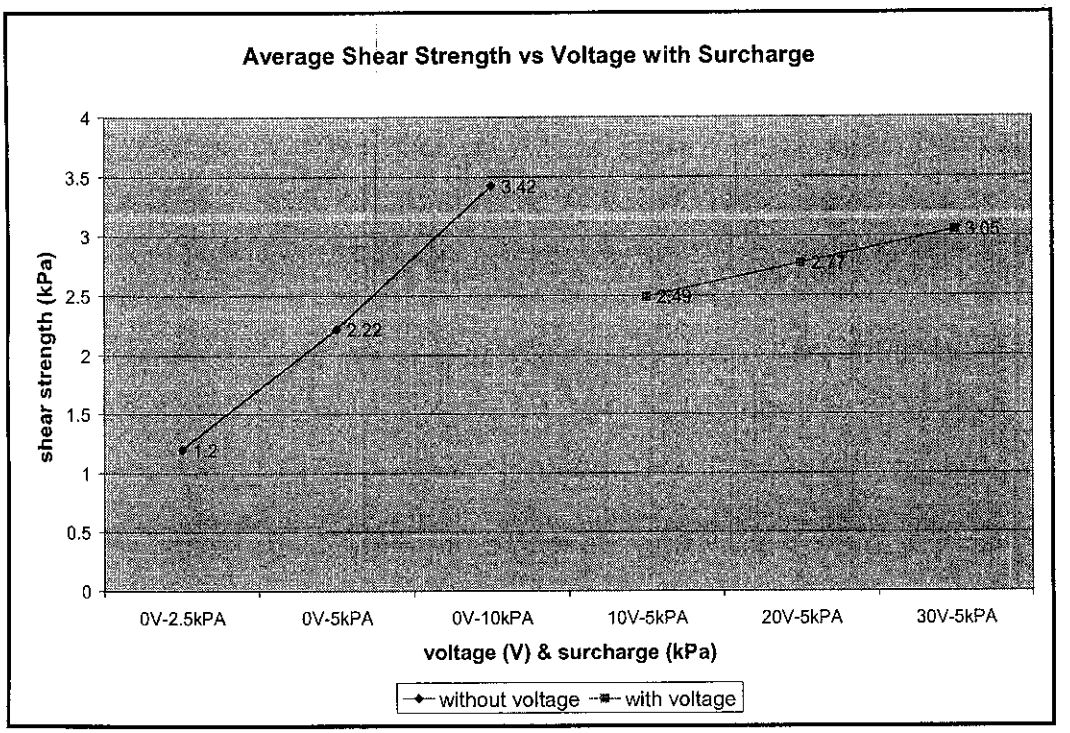


Figure 4.24 Average shear strength vs. voltage with surcharge-electroosmotic box test (2 mm)

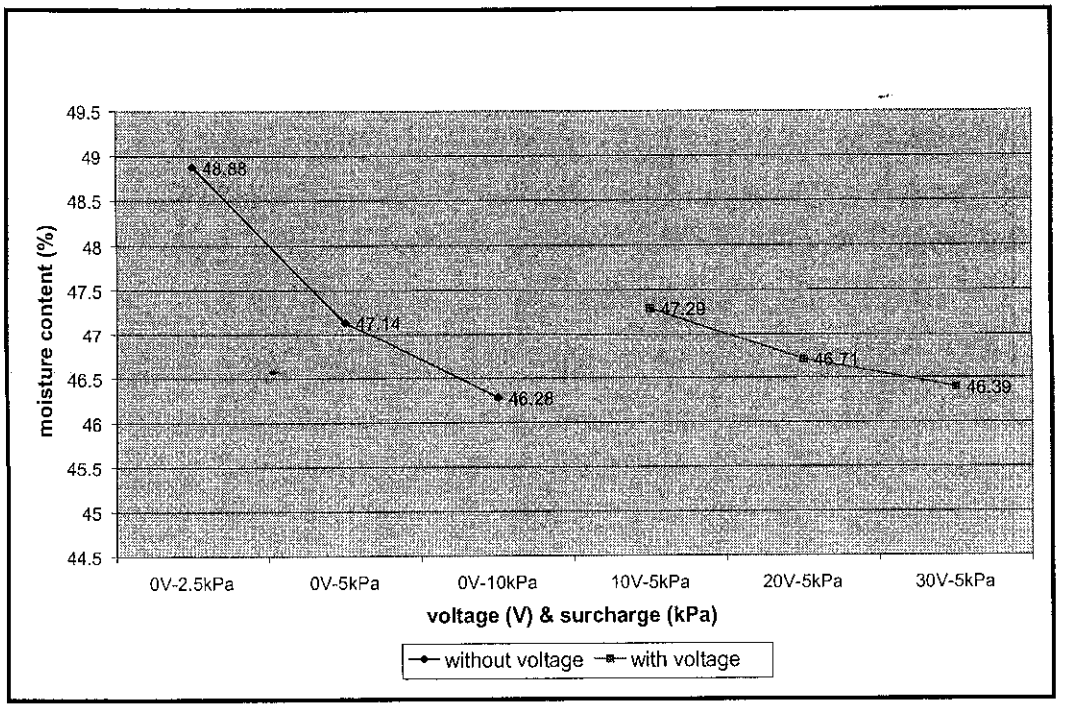


Figure 4.25 Average moisture content vs. voltage with surcharge-electroosmotic box tests (2 mm)

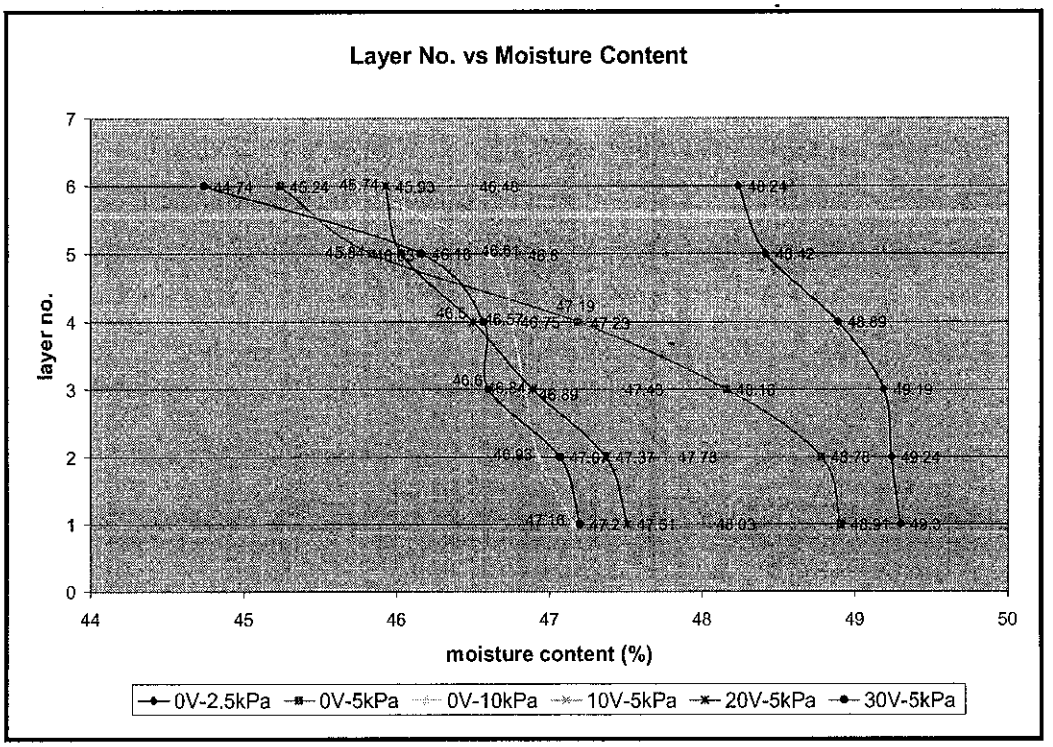


Figure 4.27 Variation of moisture content along soil samples-electroosmotic box tests (2 mm)

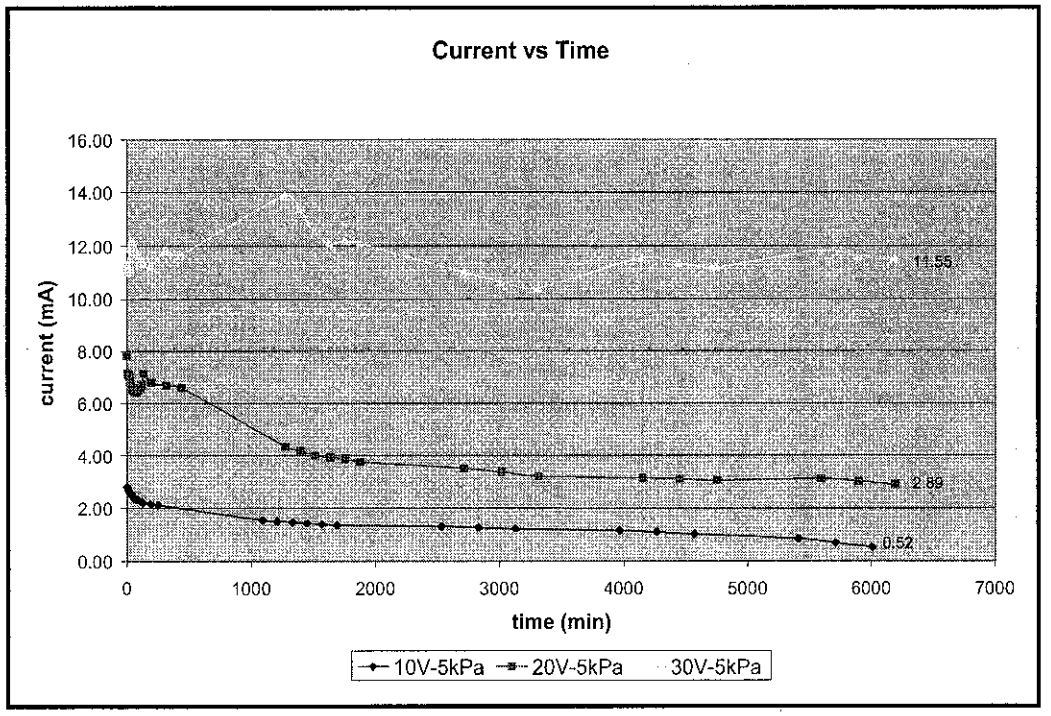


Figure 4.28 Variation of current with time-electroosmotic box tests (2 mm)

This phenomenal current behavior for 30V-5kPa test was not observed in any of the electroosmotic test previously conducted in this research. The initial increase in the current value might be due to an increase in conductivity at the anode and cathode. This increase in the region close to the electrodes might be due to the electrolysis of water resulting in the liberation of ions in the process. The ability of the current density to almost retain its initial value throughout the test period was also an indication that despite the decrease in moisture content, somehow the environment in the soil remained ionic when bigger soil particle size were used.

In addition to this, referring to equation 2.7(a) – 2.12, since steel electrodes were used, the formation of Fe^{2+} and H^{+} ions at the anode and the formation of OH^{-} at the cathode and the ability of these ions to remain ionic in an acidic environment throughout the soil sample except in the vicinity of the cathode, served possible reasons for the current density to remain high throughout the test period.

4.2.5 Electroosmotic treatment on slopes – soil passing 2 mm sieve

This category of experiment also consisted of two set of tests; one set was conducted with electrodes connection Type A and the other one was with different electrodes connection Type B.

4.2.5.1 Test using electrodes connection Type A

As mentioned earlier in section 3.2, the series of tests in slope condition was to compare the effectiveness of the electroosmotic process in treating slope with the normal flat ground condition simulated in the previous box tests. Table 4.9 shows the results generated from the various experiments conducted. Location 1, 2, 3, and 4 where samples were taken are given in Figure 3.13 in the methodology section 3.2.7. Layout of arrangement of electrodes and connection of electrodes are given in Figure 3.13 and Figure A3, respectively.

Table 4.9 Results for tests in slope condition – soil passing 2 mm sieve

Voltage (V)		0	0	0	10	20	30	20 (different electrode position)
No. of days		7	12	17	7	7	7	7
Moisture content (%)	Location 1	-	-	-	38.5	38.76	38.06	43.87
	Location 2	-	-	-	42.74	38.84	37.9	41.15
	Location 3	-	-	-	45.96	43.15	43.03	40.97
	Location 4	-	-	-	-	-	-	-
	Average	42.06	30.58	25.59	42.4	40.25	39.66	41.90
Strength (kPa)	Location 1	1.90	25.87	28.21	2.40	2.79	3.73	3.61
	Location 2	1.95	28.2	33.15	2.09	2.33	5.13	2.33
	Location 3	2.01	16.5	19.49	1.16	1.47	2.09	1.86
	Location 4	-	-	-	1.47	3.61	3.73	1.86
	Average	1.95	23.52	26.95	1.78	2.55	3.67	2.42
Maximum current (mA)		0	0	0	1.20	3.54	5.40	3.62

No surcharge was used because of the sloping nature of the soil sample and also in actual field condition, the use of surcharge on slope is not normal. In this set of tests, there were no settlement measurements taken because it is not an important criteria as far as slope stability is concerned. The results were focused more on strength gain and the removal of pore water.

Figure 4.29 shows the average shear strength gain for both electroosmotic and non-electroosmotic tests. Results shows that the average strength gain for the slope (by combining strength gain for all locations) in the electroosmotic treatment for 7 days was almost the same as what was achieved in the previous box test for soil passing 2 mm sieve. This shows the consistency of the results obtained.

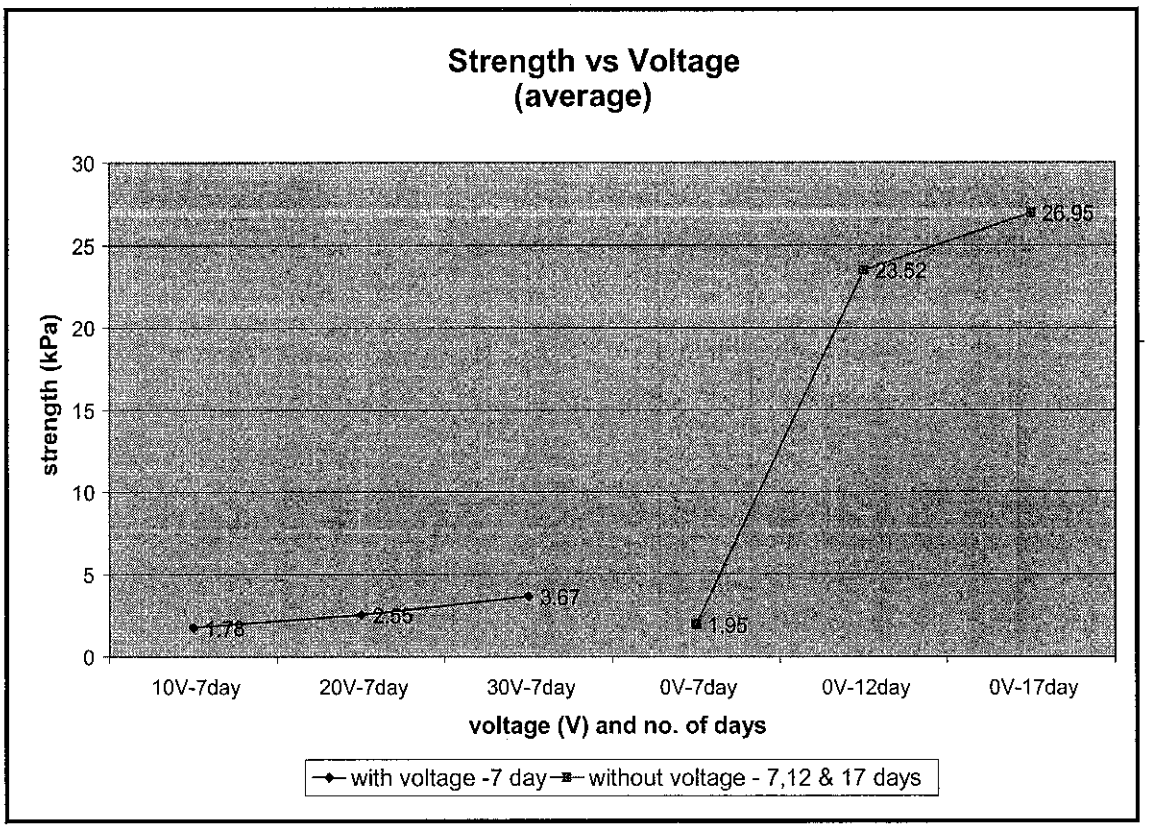


Figure 4.29 Average shear strength vs. voltage-electroosmotic test on slopes

Results for non-electroosmotic tests by exposing the slope to room environment for 12 days and 17 days produced a tremendous increase in strength. This means evaporation effect for an extended 5 to 10 days period from the initial 7 days caused enough evaporation/reduction of pore water in the slope to produce such increase in shear strength. This is justified by referring to Figure 4.30 showing the average reduction of the moisture content. The initial water content of the slope was 55% and at 12 days and 17 days tests, the final moisture content was approximately 27% and 39% lesser than the 7 days value, respectively. The actual reduction of moisture content for 0V-7days, 0V-12days, and 0V-17days from the initial moisture content of 55% was 12.94%, 24.42%, and 29.41%, respectively as shown in Figure 4.30

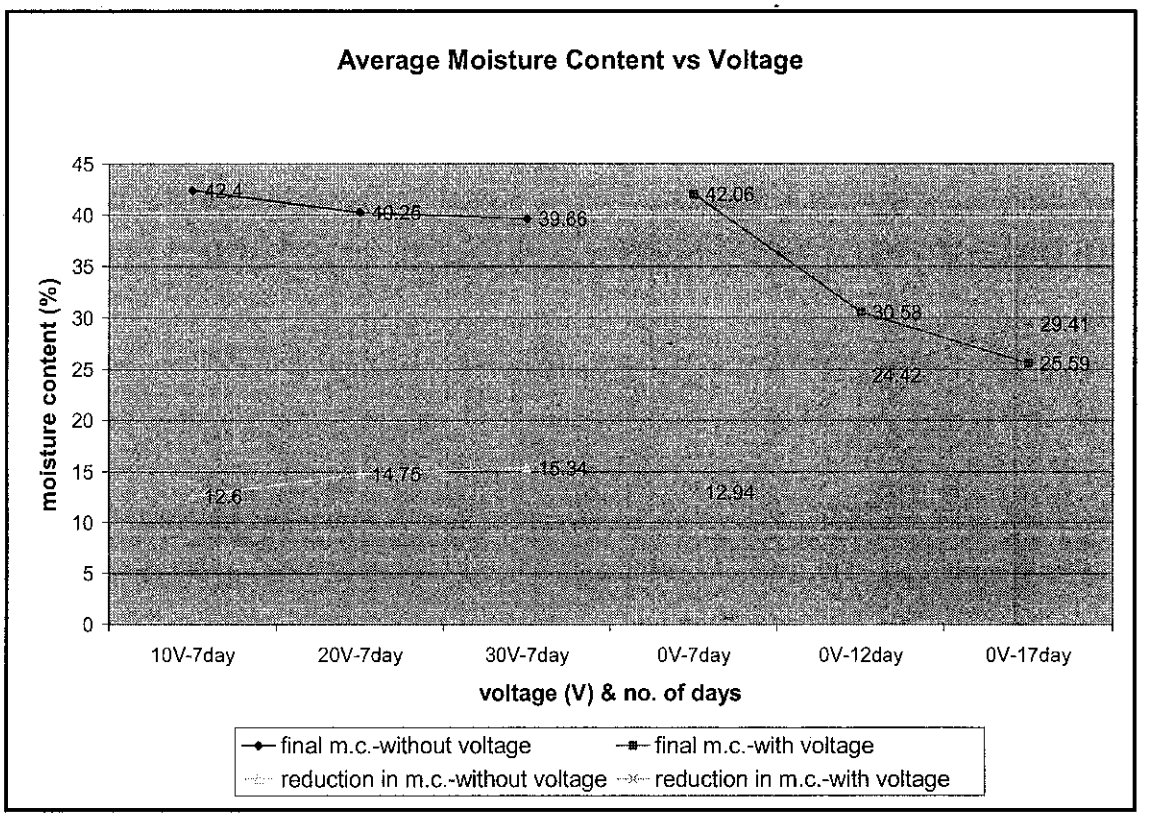


Figure 4.30 Average moisture content vs voltage-electroosmotic test on slopes

For the electroosmotic test, the range of reduction was only from 12.6%-15.34% as shown in Figure 4.30. It should be reminded here that the slope was exposed to the room environment as oppose to all the previous box and cell tests where the samples were all covered by their respective covers. Figure 4.31 shows the shear strength results for sample taken from individual locations 1, 2, and 3. Individual results were not much different from the average results except for location 3 where the strengths were somewhat smaller than the rest. This could be explained by the fact that location 3 was situated in the middle of the slope near both the cathodes where water from the anodes flowed to. In fact a huge crack resulting from the increase in moisture content was observed at the center. The higher water content at location 3 (Table 4.9) justified for the smaller shear strength if compared to locations 1, 2, and 4.

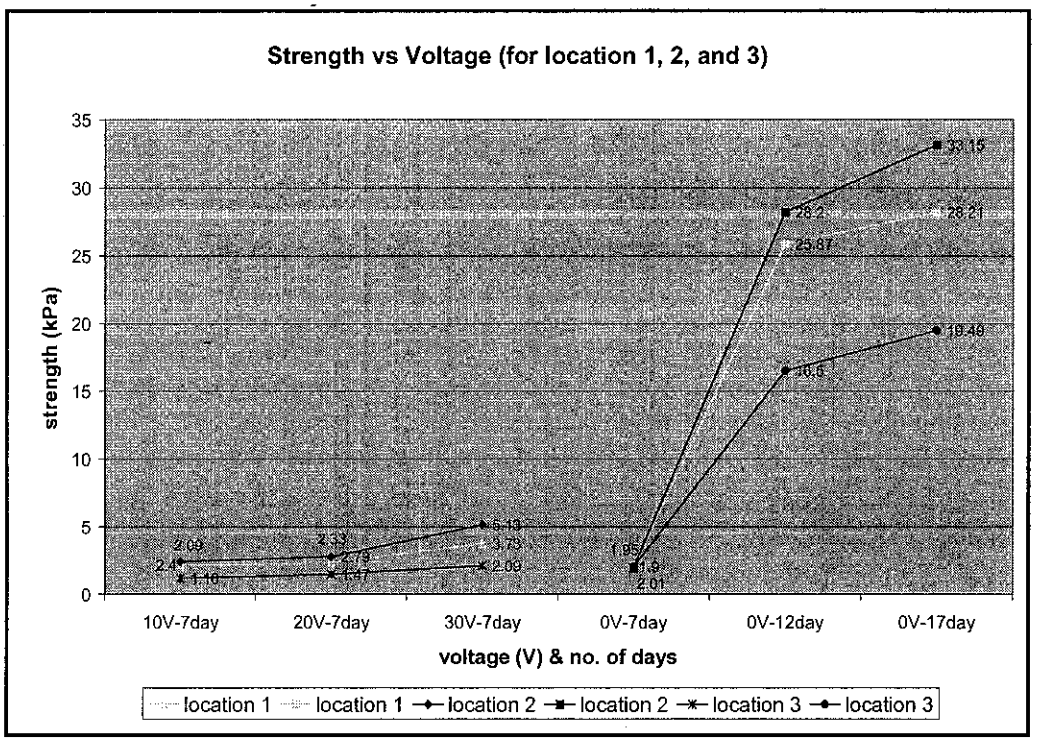


Figure 4.31 Shear strength for locations 1, 2, and 3-electroosmotic test on slopes

The sample obtained from all the locations was sliced into several parts from top to bottom and then individual moisture contents were measured to look at the water content profile along the sample. Figure 4.32 shows the profile for the average moisure content from top to bottom for location 2 of the slope. Refering to the electroosmotic tests for 10V, 20V, 30V-7days, all shows slight variations in moisture content from top to bottom except for the 10V-7days test where the difference of moisture content from top to bottom was 13.48%. Comparing this 10V-7days plot with 0V, 20V, 30V-7days plots, the effect of 10V electroosmotic treatment brought about a strange result where the moisture content at the bottom part of the slope seemed to be very low. Further analysis should be conducted as to why it was behaving as such. For the 0V-12days test, the biggest difference in moisture content was at the bottom part of the profile with a difference of 5.08%. The 0V-17days test shows a maximum difference at the top most layer with a difference of 3.17%. Comparing to the initial moisture content of 55%, it could be summarized here that the profile shows an almost uniform reduction and final moisture content from top to bottom for both the electroosmotic and non-electroosmotic tests.

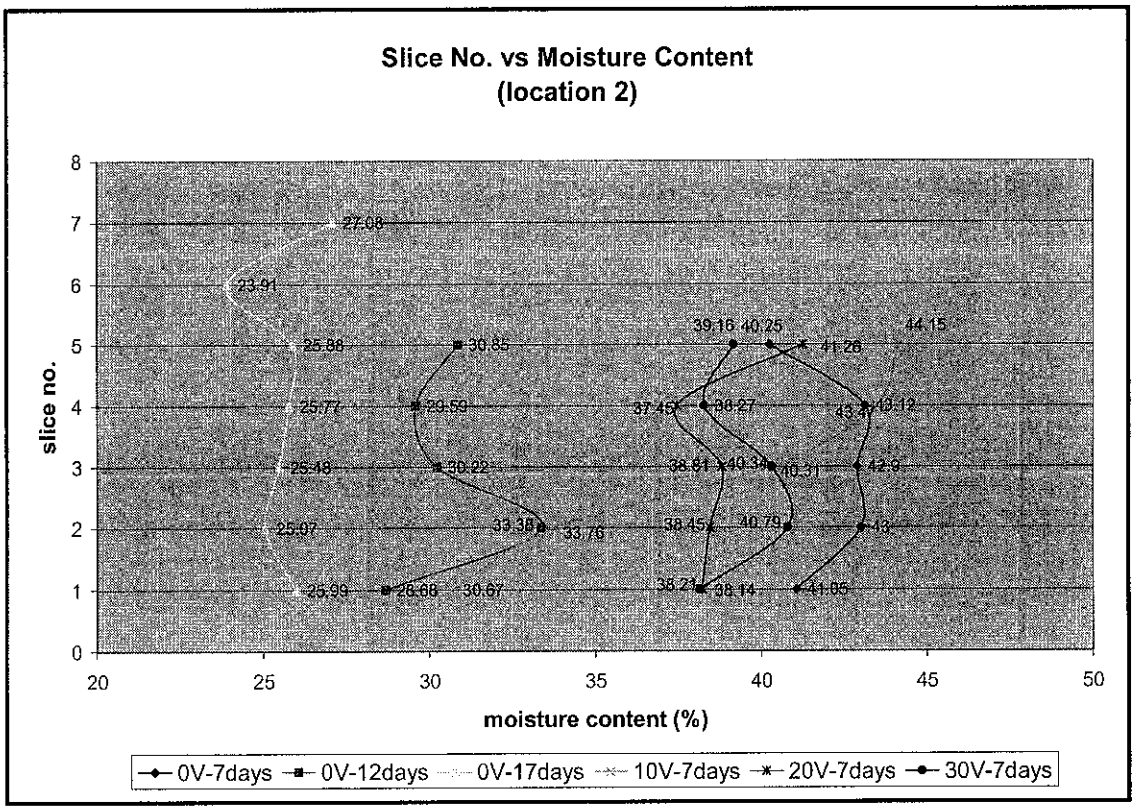


Figure 4.32 Variations of moisture content from top to bottom-electroosmotic test on slopes

A further analysis on the moisture content profile could be extracted from Figures 4.33, 4.34, and 4.35 by referring to the profiles at different locations on the effect of electroosmotic on slope for 7 days period. Except for the above mentioned 10V-7days case at location 2 (Figures 4.32 & 4.33), the rest of the profiles show relatively small variations of moisture content. Note also in all the figures, location 3 shows the highest water content as mentioned earlier because of its location of water discharge point.

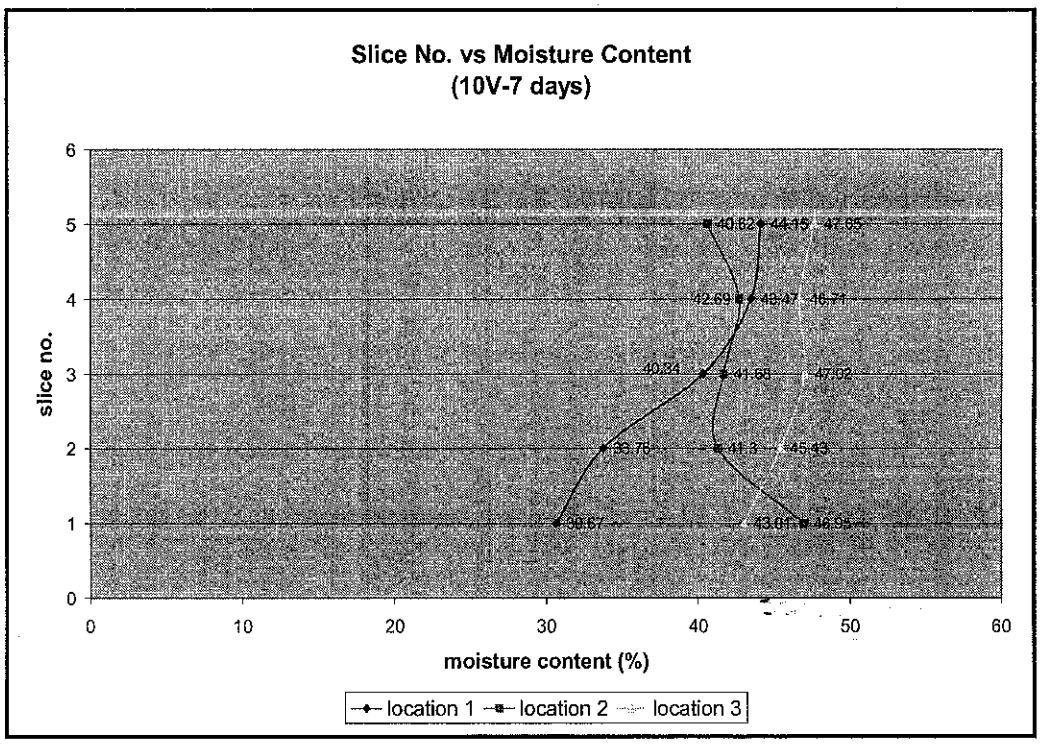


Figure 4.33 Variations of moisture content from top to bottom for 10V-7days test

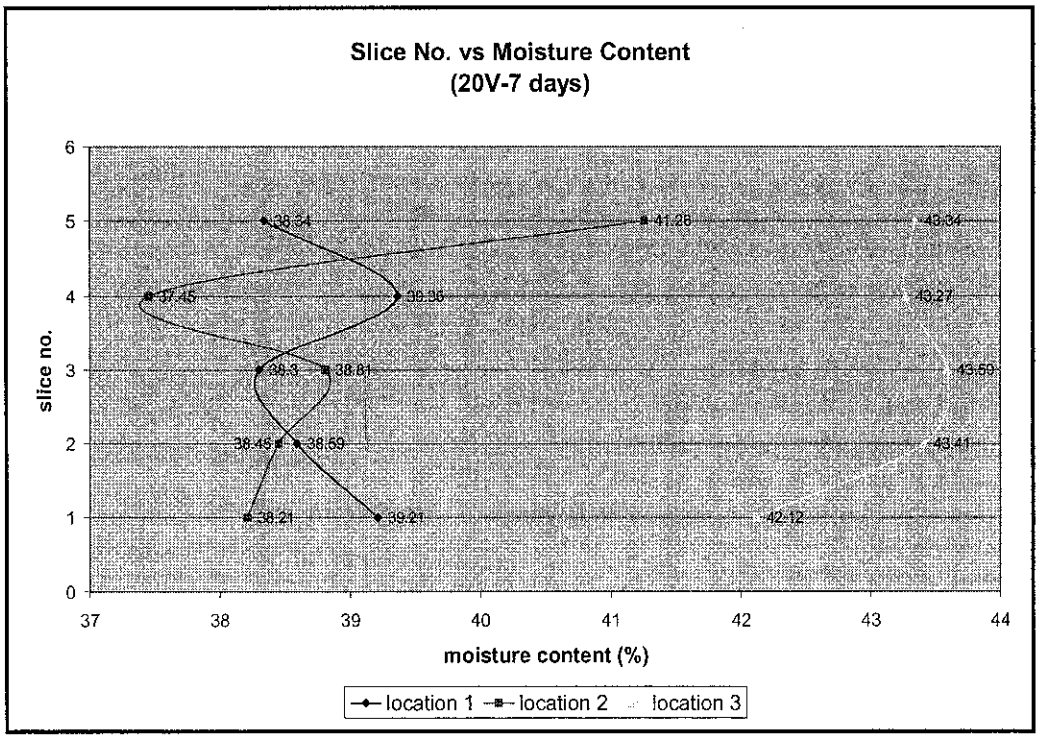


Figure 4.34 Variations of moisture content from top to bottom for 20V-7days test

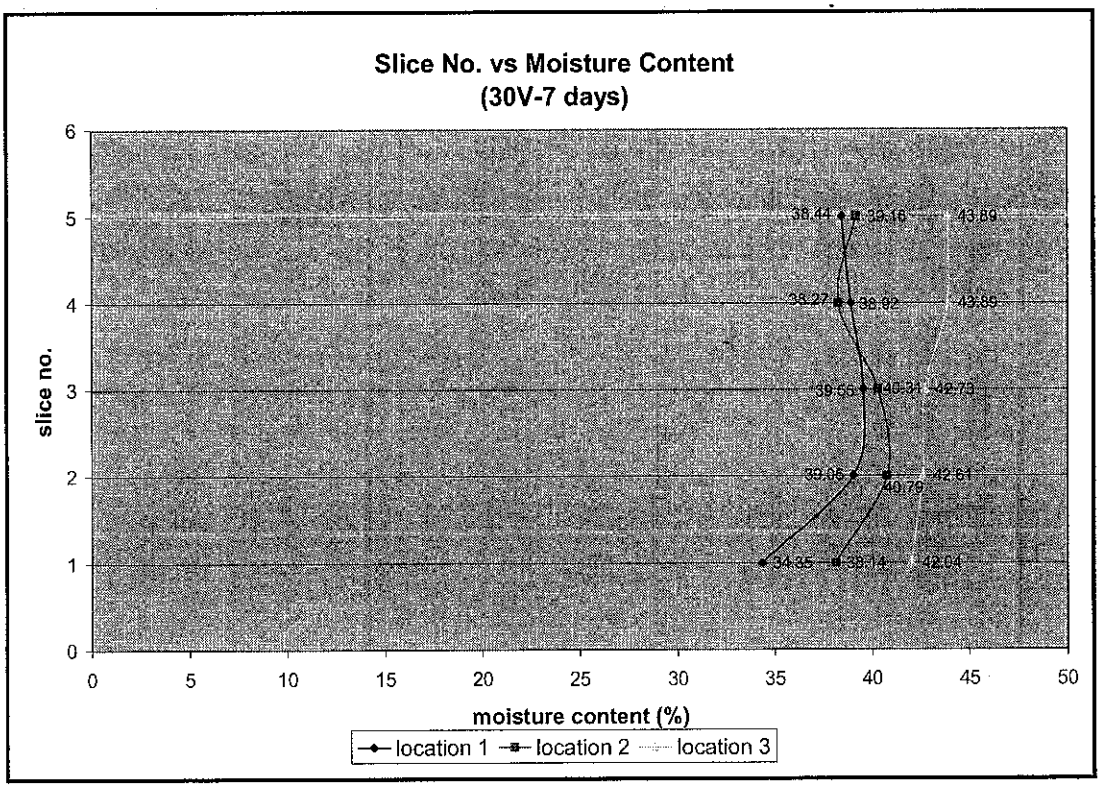


Figure 4.35 Variations of moisture content from top to bottom for 30V-7days test

Figure 4.36 shows the variations of current for location 2. The current profile is almost the same as what was acquired in the 2 mm box test with a few exceptions. The current behavior for the 20V test increased after the initial reduction and later reduced gradually to a final value of about 1.5 mA. The current behaviour for the 30V test differs slightly from what was observed in the 2 mm box test in the sense that this time instead of maintaining the initial current value towards the end, it reduced rapidly and stabilized towards the end. The comment on this behavior is the same as what was given in the previous box test case. The reducing behavior of current towards the end would probably due to the formation of neutralized zone close to the cathode. This neutral zone reduced the conductivity, increased resistivity and was a result of the movement of cations (acid front) towards the cathode and hydroxide ions (base front) towards the anode. Another factor which reduces the conductivity was due to the formation of ferrous hydroxide precipitates near the cathode which further reduced the conductivity of the soil.

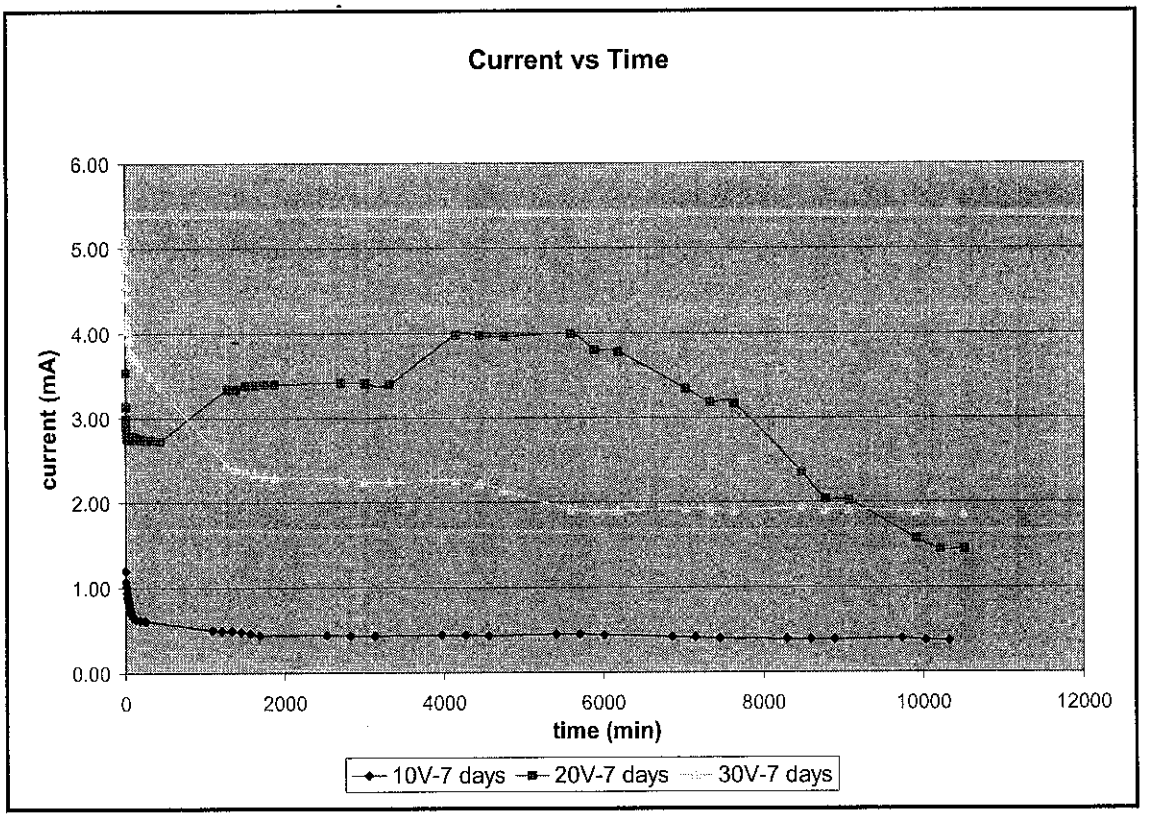


Figure 4.36 Variations of current with time-electroosmotic test on slopes

4.2.5.2 Test using different electrodes connection Type B

In the effort to study the effect of different connections of electrodes, test using Type B connection was conducted and the layout is given in Figure A4 in the Appendix section. Figure 4.37 shows the plot for the shear strength gain for locations 1, 2, 3, and 4. For locations 2, 3, and 4, the difference in shear strength was small while location 1 produced a larger strength increase. Moisture content measurements are given in Figure 4.38 where the amount of moisture content conformed with the shear strength gain shown in Figure 4.37. However, a seemingly contradicting value of moisture contents was found in location 2 for both the arrangements where both should have the same value since the shear strength obtained was 2.33 kPa for both. Overall, both connections seem to exhibit the same performance except for location 4 in connection Type A.

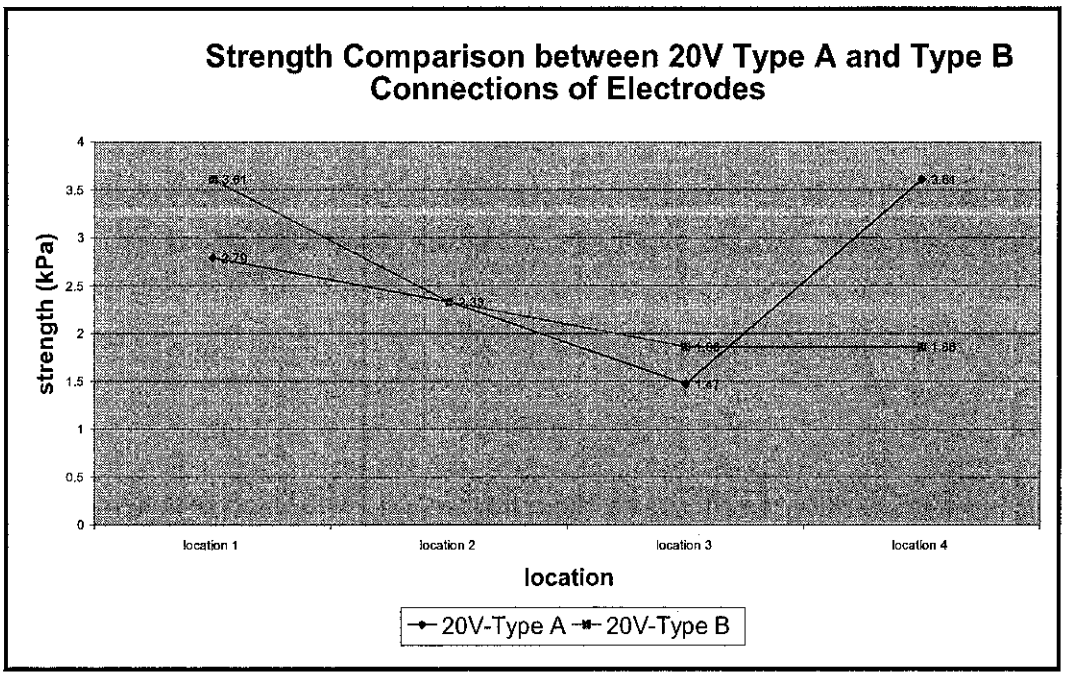


Figure 4.37 Comparison of shear strength for both connections-electroosmotic test on slopes

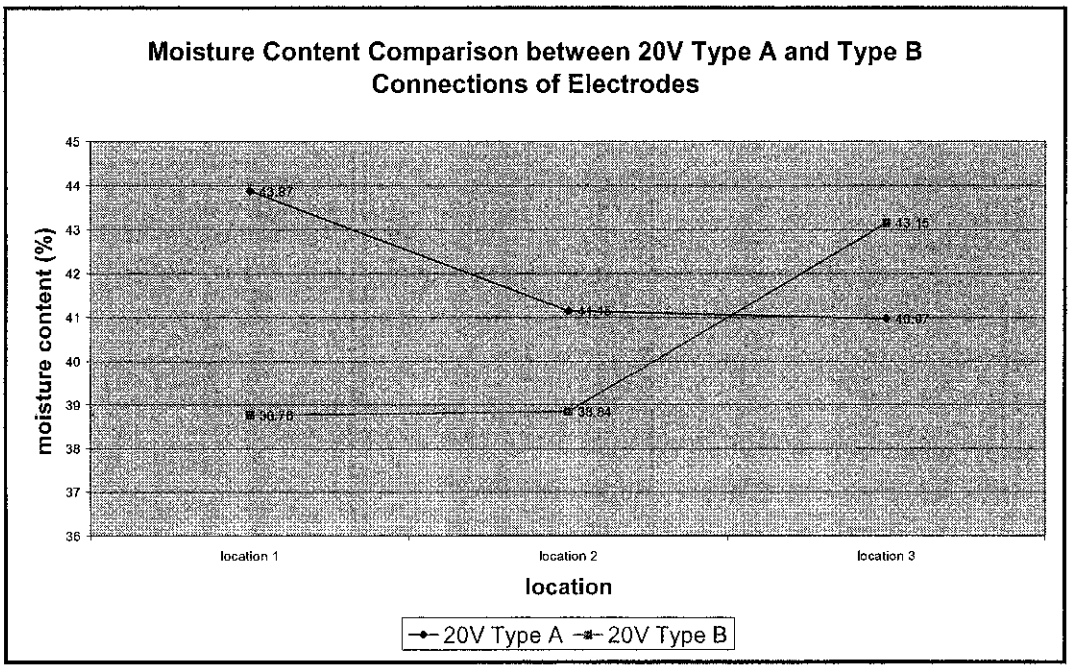


Figure 4.38 Comparison of moisture content for both connections-electroosmotic test on slopes

4.2.6 Electroosmotic cell tests – soil passing various sieve sizes

In this series of tests, electroosmotic experiments on various sizes of particles or to be more specific, particles passing certain sieve sizes were conducted. In the past, not many experiments were conducted on coarser grain material. The reason for the emphasis of clays was that, much of the stabilization effect is accomplished by the changes in electrical charge on the clay particles by base exchange. This phenomenan implies that if no clay were present, little stabilization and strengthening would occur (Adamson et al., 1967). The author feels that it is important to look into the effect of particles sizes on this kaolinite soil due to the fact that the raw sample taken at site were comprised of 53.6% sand, 38.5% silt and 5.8% clay which categorized the raw sample under sandy silt category according to the British Soil Classification system.

Table 4.10 shows the overall results for the various test conducted, all using an applied voltage of 30 volts and surcharge of 10 kPa.

Table 4.10 Results for tests using soil passing various sieve sizes

Particle Passing	Unsieved soil	2.00 mm	450 μm	150 μm	63 μm
Voltage (V)	30	30	30	30	30
Surcharges (kPa)	10	10	10	10	10
Settlement (mm)	17.92	17.81	16.31	15.03	14.41
Moisture content (%)	31.86	32.22	36.17	36.68	37.56
Strength (kPa)	6.4	8.0	9.0	12.64	15.1
Maximun current (mA)	6.13	5.77	2.81	20.79	21.89

Figure 4.39 shows the settlement results for the various particle sizes. The trend clearly indicated that bigger contents of larger size particles resulted in a larger magnitude of consolidation. The difference of consolidation/settlement between the soil passing 2 mm sieve and soil passing 63 μm sieve was about 3.4 mm which was about 20% difference. The unsieved sample and soil passing 2 mm exhibited almost the same settlement with only a small difference of about 0.11 mm. This small negligible difference was very likely due to the fact that there was only about 5% of the total soil volume was retained in the 2 mm sieve. Comparing with the cell test for soil passing 450 μm sieve conducted previously (which had the same initial moisture content of 50%), settlement for 0V-10kPa was 11.7 mm and for 30V-10kPa (conducted in this series of experiment) was 16.31 mm. The difference was 4.61 mm which was about 28% change.

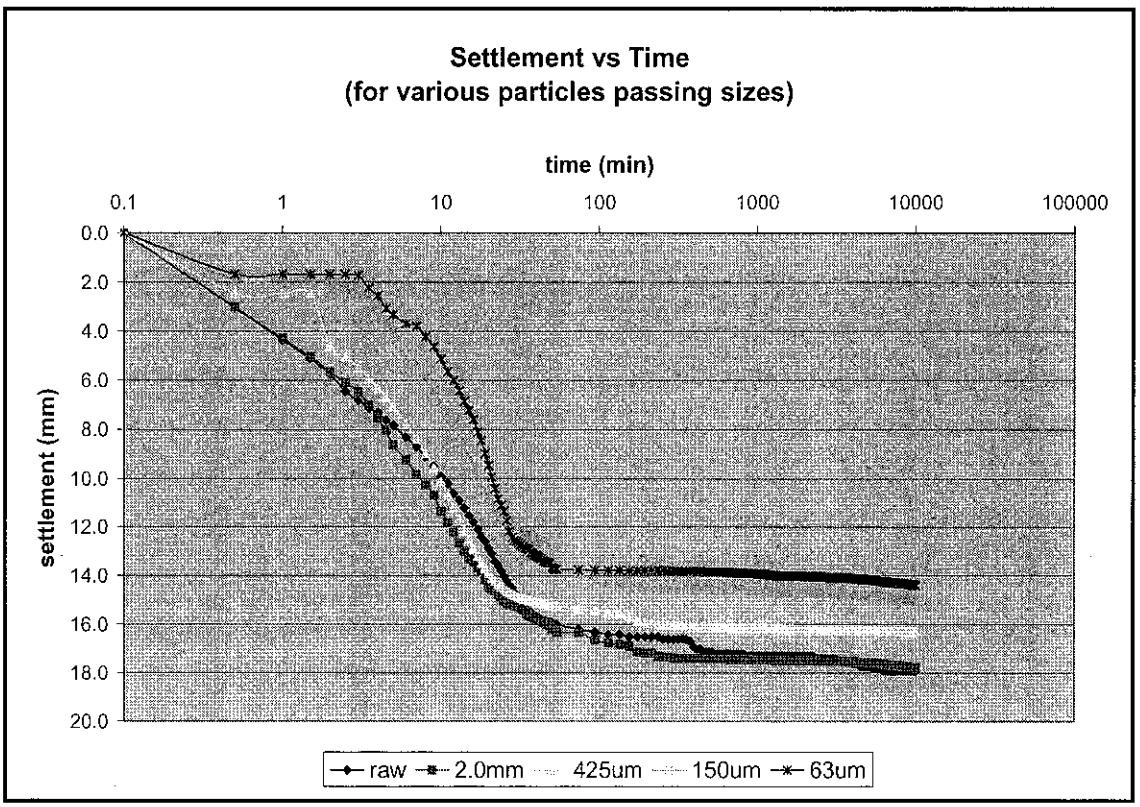


Figure 4.39 Settlement vs. time for soil passing various sieve sizes

Again the major bulk of settlement occurred within the first 100 min or so. An interesting phenomenan is shown in Figures 4.40 and 4.41. By referring to Figure 4.40, the variation in strength gain shows the opposite trend of settlement behaviour that is with bigger contents of smaller particles the gain in shear strength was more. Electroosmotic treatment on soil passing sieve size 63 μm exhibited the biggest strength gain with a difference of 7.1 kPa or 88% over soil passing sieve size 2 mm. The same behavior was observed in the moisture content plot as shown in Figure 4.41. Although the smaller size particles showed higher shear strength than the larger size particles, the final moisture content (or the reduction in moisture content) seemed to increase with increasing amount of smaller size particles.

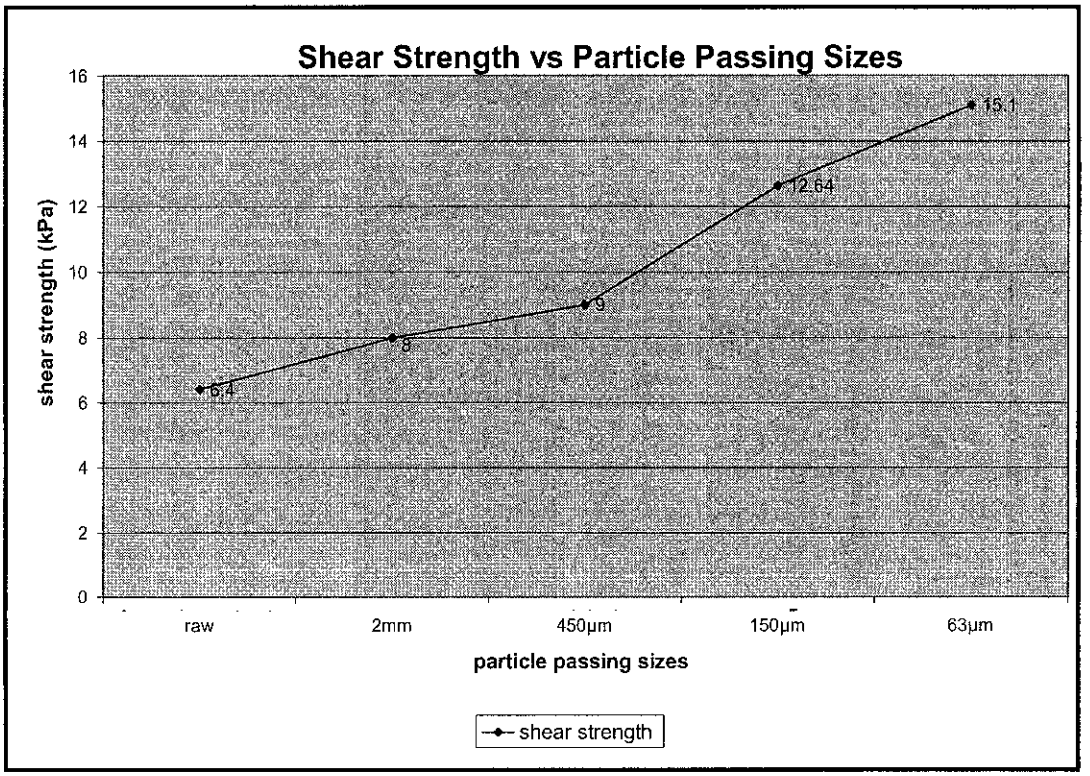


Figure 4.40 Shear strength vs. soil passing various sieve sizes

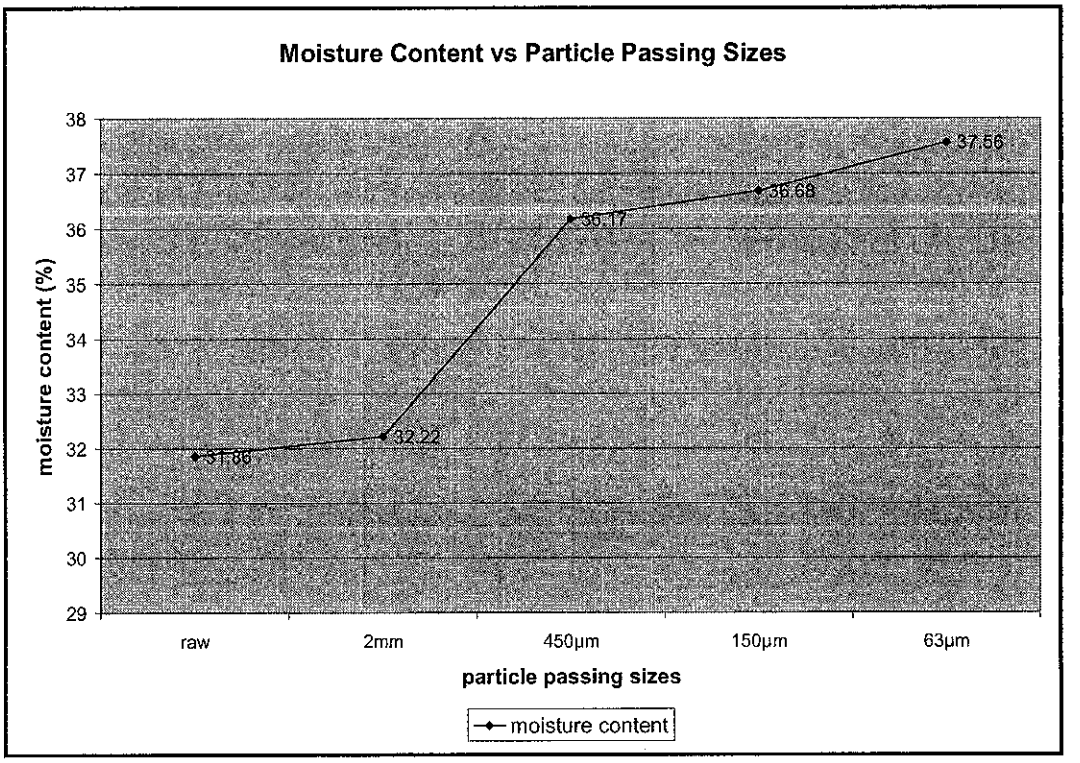


Figure 4.41 Moisture content vs. soil passing various sieve sizes

Observations by previous researchers such as Bjerrum et al. (1967) indicated that increase in shear strength of clay can be up to 400% while Wade (1976) found that in the case of silt, the strength gain was about 25% which was much lower than clay. Hamir (1997) explained that the reason could be due to the difference in the hydraulic conductivity of the two materials. The lower permeability of the clay soil results in a higher magnitude of negative pore pressure induced in it. Hence a higher magnitude of consolidation occurs in clay (smaller particle size) than in silt (larger particle size). All the statements on experimental results with respect to smaller size particles gaining better strength seems to comply to the statements made by Bjerrum (1967) and Wade (1976). However the results obtained in this research seemed to contradict to the explaination made by Hamir (1997) especially when the results on decreased settlement obtained was justified by the increased of moisture content. It could be deduced from the results that the soil passing 63 µm sieve produced smaller negative pore pressure and hence less consolidation than the soil passing 2 mm sieve but generated a contradictory higher gain in shear strength.

The author speculates that there are several factors that could explain the reasons for the contradictory behavior;

i. When comparison was conducted on the same soil type with different sizes of particles, the higher magnitude of negative pore pressure and hence the higher magnitude of consolidation which resulted in the corresponding shear strength gain in general was not the dominating factor that contributed to shear strength gain.

ii. The main contributing factor in the increase of shear strength in this set of experiments was probably due to the increase in cohesion of the soil. Early electrochemical test conducted by Adamson et al. (1967) on sandy soil + 2.5% kaolinite resulted in the increase of cohesion, *c*, from 0 lb/sq. ft. to 190 lb/sq. ft. The addition of $CaCl_2$ solution in the soil sample greatly accounted for the high increase in cohesion and mere electroosmotic treatment could to some extend have some chemical changes that caused modification and stabilizing effects including changes to the value of cohesion. Cohesion which is caused by molecular forces, depends on the number of particles and the area of contact between them (Rebinder, 1956; Adamson et al. 1966). Cohesion also depends on the thickness of the residual film of water at the contact points between particles. As films become thinner and the particles more numerous, greater contact arises between them (Zhinkin, 1960).

iii. Although the overall moisture content was more in the soil passing sieve 63 μm, the soil particles in this sample was more. It was possible that the residual film of water (diffuse layer) was thinner and hence the contact points between the small particles were better causing better cohesion.

iv. Smaller size particles will normally exhibit a better charge in surface forces and better cation exchange capacity. Higher valence cations replace those of lower valence, and larger sized cations replace smaller cations of the same valence (Little 1987). In fact, researchers found that electrokinetic works more efficiently in fine-grained materials where the surface properties of particles are dominant. There might just be a possibility that this phenomenon took place better in the

smaller size particles of the same soil type. The better surface forces and cation exchange capacity accounted for a better flocculation/coagulation and some degree of stabilization.

Figure 4.42 shows current variations between the various particle sizes. The trend of reduction of current seems to be normal with all final current seem to converge to a value of approximately 0.5 mA. Note that the initial current value was higher in the predominantly small size (especially for soil passing 63 μm sieve) particles than the predominantly larger size particles.

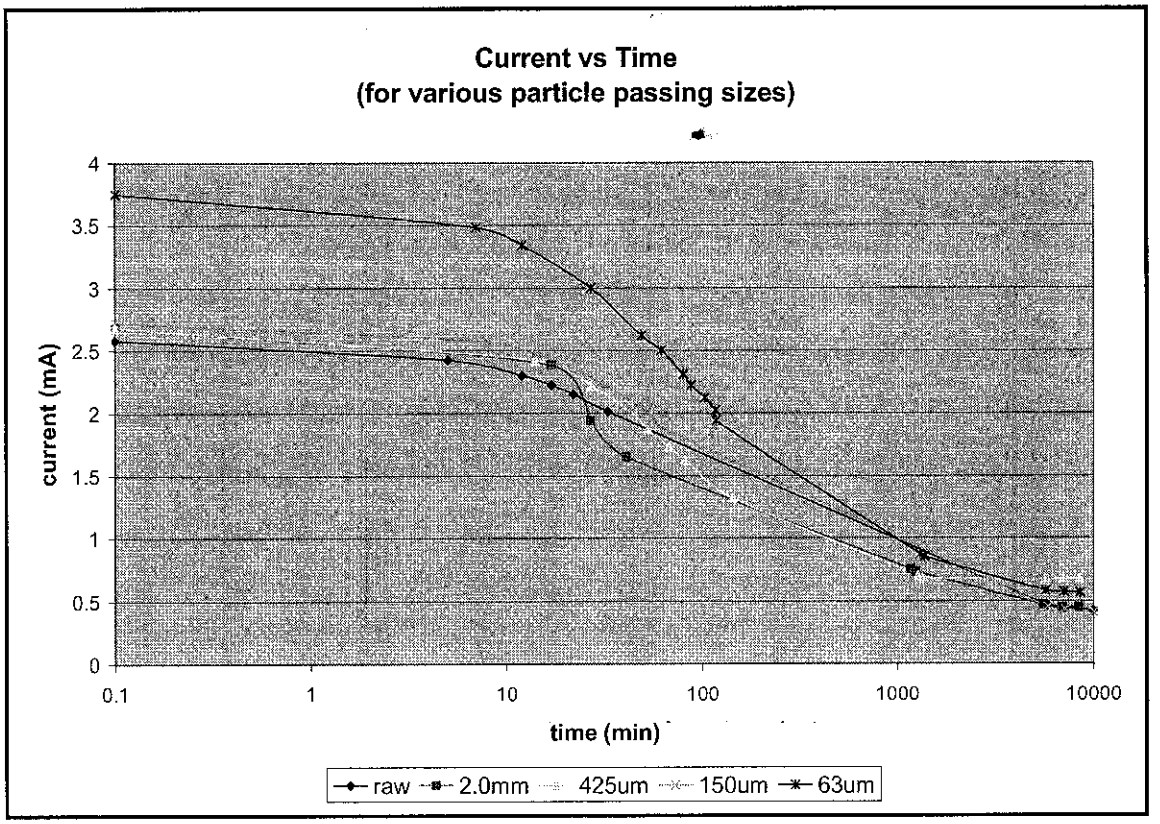


Figure 4.42 Variation of current vs. time-soil passing various sieve sizes

4.2.7 Electroosmotic box tests – various electrode spacings

A set of electroosmotic tests without any surcharge was conducted to look into the effect of different electrode spacings. Table 4.11 gives all the corresponding results.

Table 4.11 Results for tests using different electrode spacings-(2mm)

Spacing of electrodes	450 mm			225 mm			112.5 mm		
	Ano.	Cen.	Cat.	Ano.	Cen.	Cat.	Ano.	Cen.	Cat.
Voltage (V)	30	30	30	30	30	30	30	30	30
Surcharge (kPa)	0	0	0	0	0	0	0	0	0
Moisture content (%)	31.13	31.83	32.67	30.0	30.93	30.92	29.2	-	30.0
Strength (kPa)	3.1	3.5	2.91	4.1	3.5	3.5	5.0	-	4.1
Maximum current (mA)	0.45			1.75			2.61		

Moisture content and shear strength were taken at anode, center, and cathode of each test. Figures 4.43 and 4.44 show the shear strength variations and moisture content for all the different spacings. It was observed that the smaller spacing gave rise to a bigger strength gain and bigger reduction in moisture content. Improvements at anodes were better than that of cathodes and centers in all the tests. In field application, the spacing between electrodes depends primarily on the design and the urgency of the treatment. It may also depend on the available power supply. The commonly used spacing-ranges from about 1 to 6 m, (Cassagrande, 1983). Figure 4.45 shows the current variation for test on all the tests with the lower spacings generated higher current value. This was obvious as shorter spacing caused shorter conductive path of electrical current and hence less resistance.

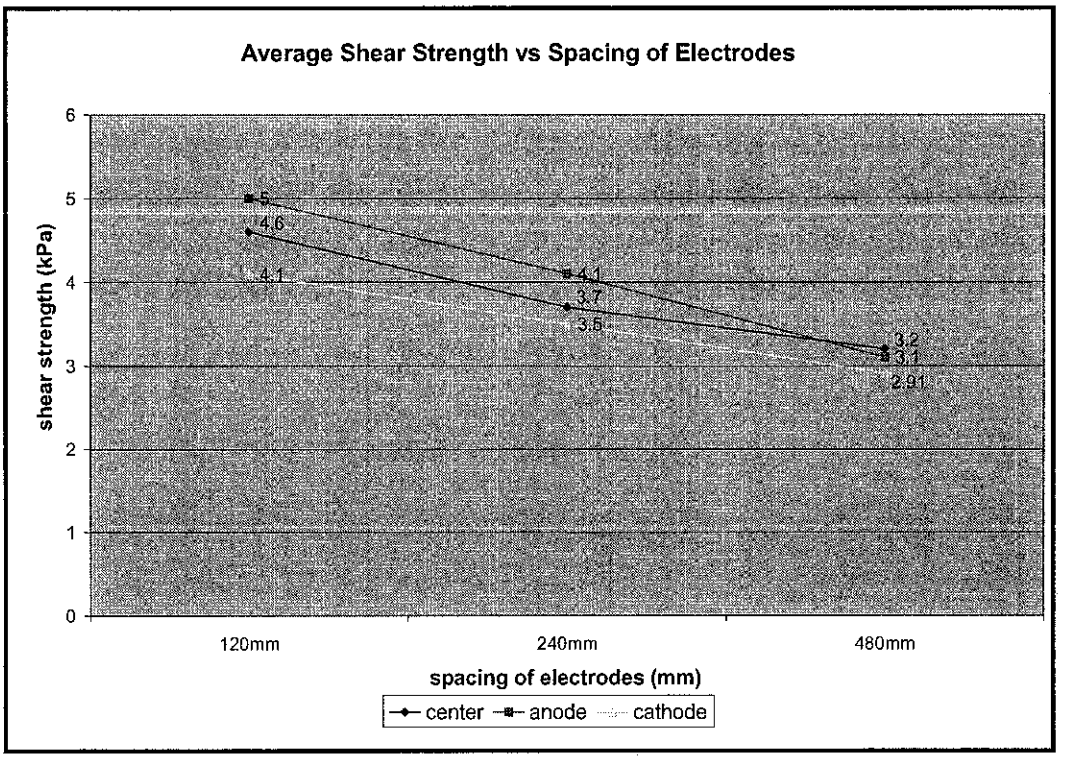


Figure 4.43 Average shear strength for different electrode spacings

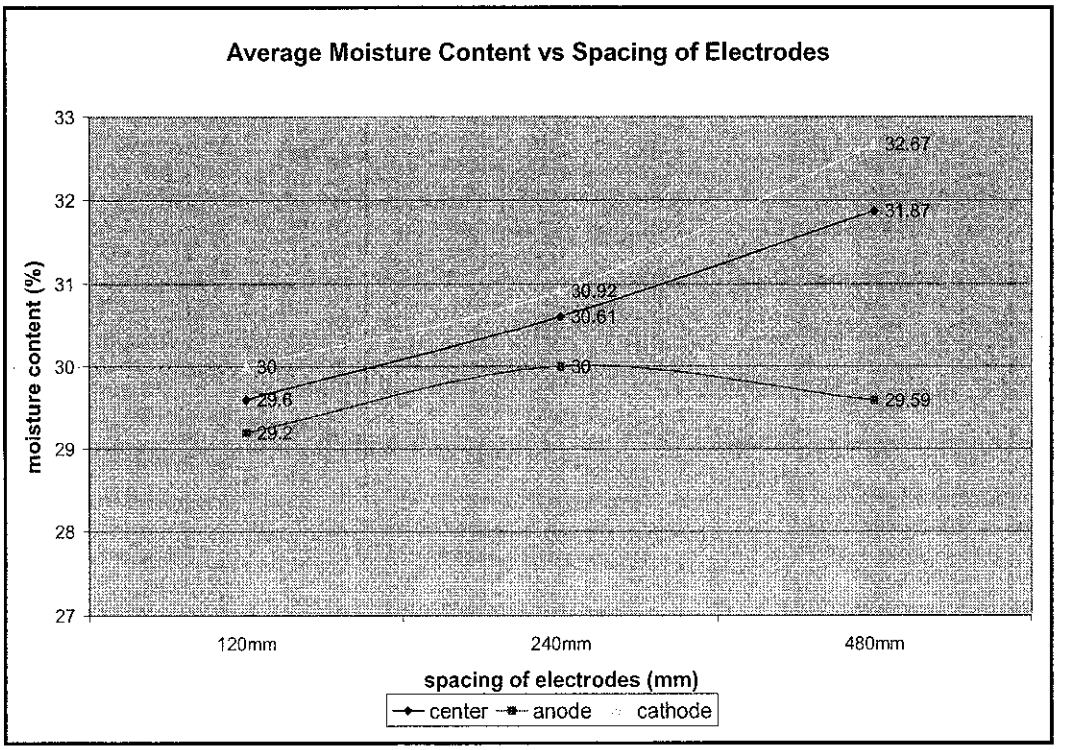


Figure 4.44 Average moisture content for different electrode spacing

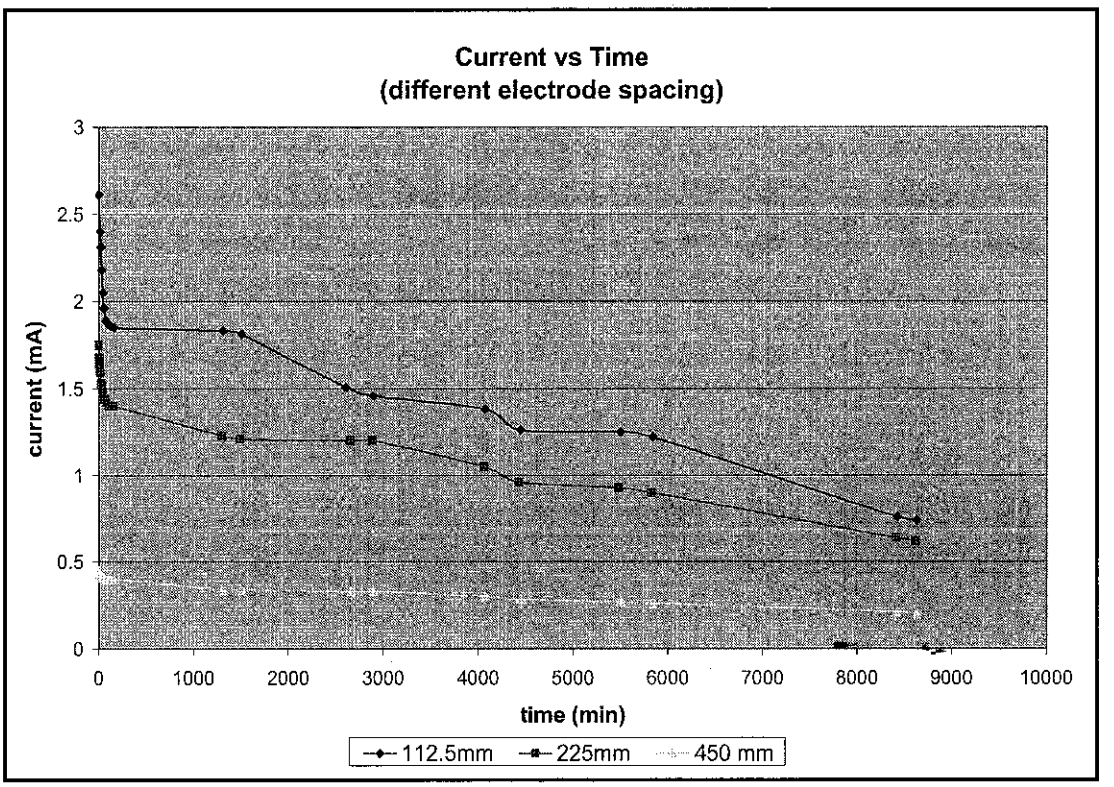


Figure 4.45 Variation of current with time for different electrode spacings

In conclusion, although the variations of strength gain and reduction of moisture content was not much, tests shows that improvement was generally better for shorter spacings of electrodes. In fact in many practical application, the spacing of electrodes is one of the governing factors contributing to the effectiveness of the treatment.

4.3 Electrochemical Tests

4.3.1 Electrochemical horizontal cell tests – soil passing 2mm sieve

Beginning from this test onwards, with a few exceptions, all the subsequent treatments had chemicals added/injected into the system. In fact special focus was given to the electrochemical aspects of treatment due to its ability to enhance the properties of soil better than in the electroosmotic process. The two main properties which were given special attention in the subsequent electrochemical experiments were of course the strength gain and reduction in moisture content. No reading on settlement/consolidation was taken because it was expected that the main improvement would be due to physico-chemical changes and not due to merely consolidation.

Table 4.12 shows the overall results for all the tests conducted. Table 4.12 shows results mainly obtained from samples injected with $CaCl_2$, $Ca(NO_3)_2$ and $Ca(OH)_2$ using different voltages and different molarities. A test on soil sample with $Mg(OH)_2$ was also included. A comparison was also made with tests using distilled water which is included in the table.

Figure 4.46 shows the results on strength gain extracted from Table 4.12. In all the tests, the shear strengths obtained were larger at the location near anodes than at cathodes. 2mol-$CaCl_2$-100V test gave the largest reading of 40.1 kPa which was in the firm soil category according to British Standard. The strength gain when compared to the test using distilled water was more than double which was about 101% increase. 1mol-$CaCl_2$-100V test increment came second with about 71.2% increase. From the three tests conducted on $CaCl_2$ using 30V, test 3mol-$CaCl_2$ gave smaller shear strength value than 1mol and 2mol tests. The reason for this behavior is discussed further on page 180.

Table 4.12 Results on electrochemical tests using different chemicals, voltages and molarities

Type of Test	$CaCl_2$ 1mol		$CaCl_2$ 2mol		$CaCl_2$ 3mol		$CaCl_2$ 1mol		$CaCl_2$ 2mol		Distilled Water		Distilled Water	
Voltage (V)	30		30		30		100		100		30		100	
Surcharges (kPa)	0		0		0		0		0		0		0	
Moisture content (%)	A	C	A	C	A	C	A	C	A	C	A	C	A	C
	32.1	33.3	31.58	34.1	31.57	34.3	28.0	29.8	24.79	30.52	31.89	32.3	28.18	28.97
Strength (kPA)	12.74	8.0	14.0	7.0	8.0	5.6	34.26	22.84	40.1	-	6.4	6.4	20.0	16.3
Maximum current (mA)	118.3		68.2		97.2		217		653		2.28		7.77	
Type of Test	$Ca(OH)_2$ 1mol		$Ca(NO_3)_2$ 1 mol		$Ca(OH)_2$ 2mol		$Ca(NO_3)_2$ 1mol		$Ca(OH)_2$ 1mol		$Mg(OH)_2$			
Voltage (V)	30		30		30		100		100		30			
Surcharges (kPa)	0		0		0		0		0		0			
Moisture content (%)	A	C	A	C	A	C	A	C	A	C	A	C		
	32.63	33.92	31.44	34.9	32.11	31.0	26.46	27.9	30.25	32.48	32.6	33.96		
Strength (kPa)	7.0	4.1	8.62	7.07	7.0	4.37	34.26	-	14.21	8.0	4.1	4.1		
Maximum current (mA)	5.71		74.5		2.26		673.7		36.5		1.84			

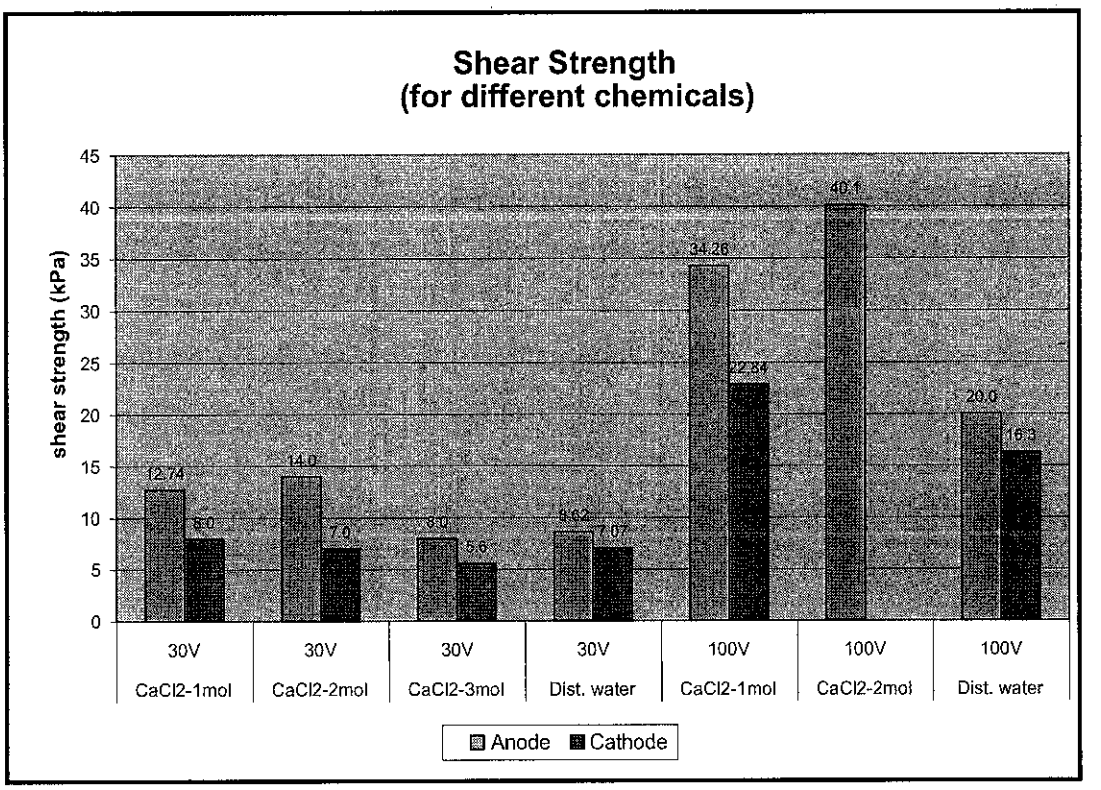


Figure 4.46 Shear strength gain for samples using $CaCl_2$ and distilled water-horizontal cell test

Figure A5 in Appendix A shows a picture taken for 2mol-$CaCl_2$-100V test showing the condition of the sample after treatment. An XRF test was also conducted on the sample taken close to the the anode. Close observation were made on the portion of black formation and the normal white soil portion. From the XRF results, comparison between tests for 2mol-$CaCl_2$-100V, distilled water and untreated soil samples were made to look into the changes of contents in the compounds for all the three soil samples. Five specific compounds were tabularized in Table 4.13 to prove the effectiveness of electrochemical treatment in stabilizing soil as oppose to mere electroosmotic treatment.

Table 4.13 Percentage contents of compounds in soil sample after treatment

	Al_2O_3 (%)	SiO_2 (%)	CaO (%)	CuO (%)	Fe_2O_3 (%)
2mol $CaCl_2$ -100 V (portion with black formation)	21.2	67.6	1.35	3.30	0.693
2mol $CaCl_2$-100V (white portion of sample)	25.3	60.8	2.08	0.426	0.985
Distilled water-100V	30.5	61.6	0.169	0.0387	0.588
Untreated sample	30.7	61.7	0.158	0	0.772

By comparing the variations in percentage contents of compounds, results clearly show significant changes which was attributed to the high chemical activities during the process of electrochemical treatment. This chemical activities contributed to the high strength gain causing significant modification and stabilizing effect in the soil sample. Table 4.13 also shows that in the case of 2mol $CaCl_2$-100V test (portion with black formation), a reduction of 9.5% of Al_2O_3 from the original 30.7% (in untreated soil) occurred and was dissolved and separated into individual ions. Reduction of SiO_2 was about 5.9%. Note that the amount of Al_2O_3 and SiO_2 were approximately the same in both untreated sample and electroosmotic test using distilled water. The dissolved Al_2O_3 and SiO_2 then reacted with the free calcium ions injected through the anode and formed hydrated aluminate (CAH) and hydrated silicate (CSH) which were indicated by the 2.08% content of CaO, an increase of 1.92% and 1.91% content from untreated soil and electroosmotic test respectively.

A small reduction of SiO_2 in the white portion sample of test 2mol $CaCl_2$-100V shows that small amount of CSH was also formed. The formation of crystallized CAH and CSH compounds were the major contributing factor of strength gain in this electrochemical process. Another contributing factor also came from the precipitation of compounds such CuO and Fe_2O_3 in the sample. An increase in the formation of CuO and Fe_2O_3 precipitates are shown in Table 4.13 for the 2mol-$CaCl_2$-100V sample while practically

no CuO was found in the untreated soil and only 0.038% in the electroosmotic test sample. Although in this particular test no reading of pH was taken but theoretically an acidic environment would have prevailed especially in the vicinity of the anode. However, one could see that the reason for a higher reduction in Al_2O_3 contents than that of SiO_2 was due to the fact that the dissolution of alumina could have occured in small quantities at pH less than 7. Then it starts to increase significantly at a pH>8 and reaches a maximum at pH>10. It should be noted dissolution of silica is negligible at pH<8 and reaches a maximum at pH>10 (Baker, 2004).

One important argument which warrant special attention was the fact that in normal situation whereby the improvement at cathode in electrochemical test should be more than at the anode (as observed by many researchers), this phenomena did not prevail in all the tests conducted as given in Table 4.12 and Figure 4.46. This could probably be attributed to the short sample tested where the distance between anode to cathode was only about 125 mm in the horizontal cell tests. Therefore, when very short spacing between anode and cathode was used, little difference of properties in the soil sample between both electrodes in terms of strength gain, reduction of moisture content etc. were observed (this was further proven in the subsequent 150 mm spacing electrochemical box test). What happened was that the whole 2mol-$CaCl_2$-100V sample was dominated with a low pH condition (acidic condition pH<7) with only a very small portion having low alkaline condition very close to the cathode which was not enough to generate the normal results associated with alkaline environment such as high precipitates and increase formation of hydrated silicates and aluminates contributing to strength gain. Interesting Note that even in such an environment, significant amount of precipitations and formation of hydrated aluminate and silicate gels still occurred as proven in Table 4.13.

Referring to the three tests on $CaCl_2$ using 30V from the same table, it shows that test 3mol-$CaCl_2$ gave smaller shear strength value than the 1mol and 2mol tests. The results show that at high concentration of $CaCl_2$ using 30V, the enhancement did not increase but rather decreased. Equations 2.29 and 2.30 clearly indicated that the total mass flow of chemical species, J_i, and charge (ions) flow in an electric field, among others, depends on the concentration of chemical and voltage of the treatment. Results show that for both the

2mol-$CaCl_2$-30V and 2mol-$CaCl_2$-100V tests, the enhancement of soil stabilization was better than the 1mol test, hence conforming to the above formula. However, the result for 3 mol-$CaCl_2$-30V test was even less sucessful than that of the treatment using distilled water. The explanations might be that very high concentration would results in undesirable high production of H^+ ions causing extremely acid condition throughout the sample which did not allow for any formation of hydrated aluminate, silicate or precipitation of any insoluble compounds. Another reason could also be due to the fact (as stated by some researchers) that zeta potential decreases with increasing electrolyte. As given in equations 2.30 and 2.31, since charge ions flow is dependant on conductivity, σ which is a function of zeta potential, z_i, at a certain increase in electrolyte concentration the zeta potential and hence ionic migration became relatively low to sufficiently affect in the stabilization process. It is reported in electroosmotic dewatering process, increase in electrolyte concentration tends to decrease the efficiency in inactive clays such as kaolinite (Hamir, 1997). Although the decrease in efficiency was related to electroosmotic process, there might be a possibility that a certain increase in electrolyte concentration have the adverse effect in electrochemical treatment as well.

Figure 4.47 shows the corresponding reduction in moisture content for the tests in Table 4.12. Note that the final moisture content for 3mol-$CaCl_2$-30V test at anode was just about the same as what was obtained in the 1mol-$CaCl_2$-30V and 2mol-$CaCl_2$-30V. In fact the moisture content at cathode was higher than that of the other two tests. This again, was an indication of the inefficiency of using higher electrolyte concentration in dewatering process. In general, Figure 4.47 shows a general trend of decreasing moisture content with increasing shear strength at both anodes and cathodes.

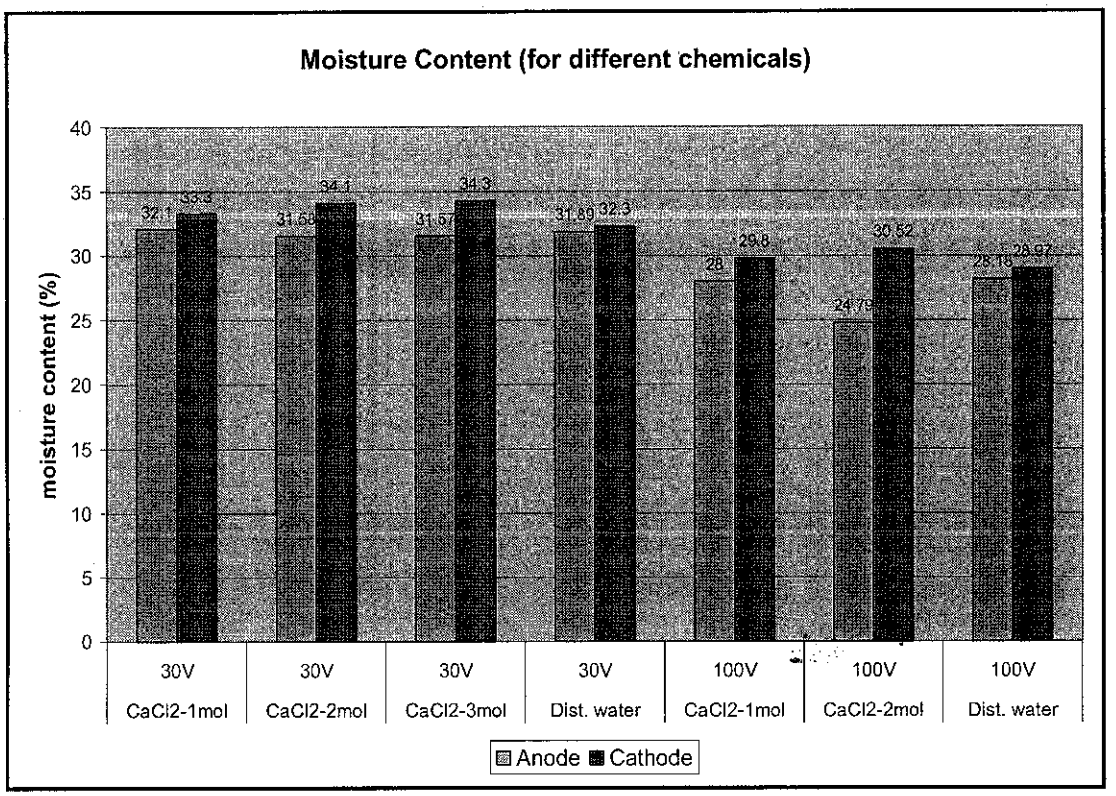


Figure 4.47 Moisture content in samples using $CaCl_2$ and distilled water-horizontal cell tests

Figure 4.48 shows the results of shear strength gain from Table 4.12. The highest strength increase was obtained in the test on soil sample using 1mol-$Ca(NO_3)_2$-100V with strength gain of 34.26 kPa which is an increase of 71.3% than using distilled water-100V. Note that the increase in strength was the same with test using 1mol $CaCl_2$-100V (Figure 4.46). The increase in shear strength for the 1mol-$Ca(NO_3)_2$-30V test was only about 20% at anode and 32% at cathode when compared to test using distilled water-30V. The lowest value was obtained using 1mol-$Mg(OH)_2$-30V with a reduction of shear strength of about 50% from the test using distilled water -30V. Likewise the tests using 1mol-$Ca(OH)_2$-30V, 2mol-$Ca(OH)_2$-30V and 1mol-$Ca(OH)_2$-100V all produced lower strength gain than that of electroosmotic test using distilled water. These results gave an important indication that for the particular kaolinite soil sample used in this research, the effect of using magnesium hydroxide and calcium hydroxide did not produce any desirable

electrochemical effects and rather their effectiveness in stabilizing kaolinite soil was even less than that of electroosmotic method.

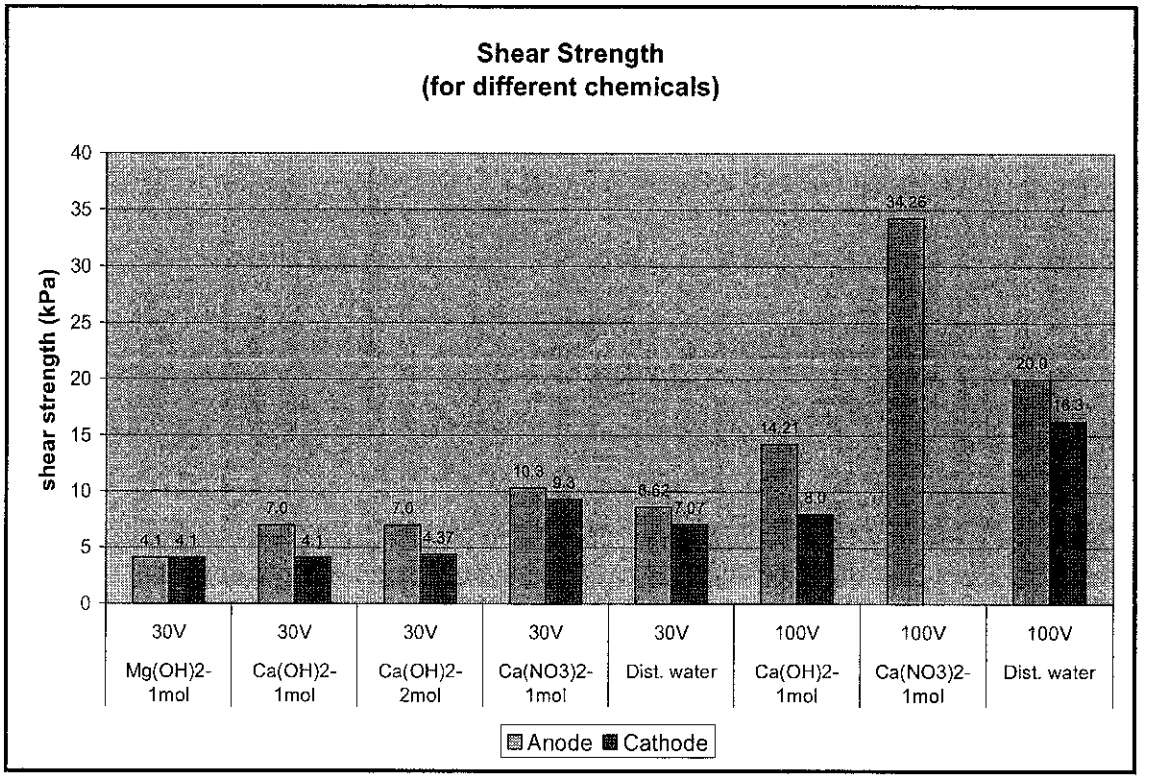


Figure 4.48 Shear strength gain for samples using $Ca(NO_3)_2$, $Ca(OH)_2$, $Mg(OH)_2$ and distilled water-horizontal cell tests

The reason lies in the fact that both $Ca(OH)_2$ and $Mg(OH)_2$ were weak bases and they were not very soluble in distilled water. Therefore both hydroxides produced only few Ca^{2+}, Mg^{2+} and OH^- ions which when injected at anode caused the hydroxide to combine with H^+ ions generated. This caused more formation of H_2O at anode which accounted for the slightly increase in moisture content at anode in tests using $Ca(OH)_2$ and $Mg(OH)_2$ compared to the test using distilled water as shown in Figure 4.49. The small amount of Ca^{2+} and Mg^{2+} ions remained ionic throughout the sample due to high acid environment causing the conductivity in the soil-electrolyte system to be higher than the test using distilled water. This is indicated in Table 4.12 and Figure 4.50 where the initial and maximum current achieved for both $Ca(OH)_2$ and $Mg(OH)_2$ tests were larger than

that in test using distilled water. The acid environment and small amount of Ca^{2+} and Mg^{2+} ions resulted in the inability of the system to produce CAH and CSH compounds and insoluble precipitates compared to those using $Ca(NO_3)_2$ and $CaCl_2$ solutions. Modification and some stabilizing effect due to a more flocculated structure produced from multivalent ions in the clay structure replacing hydrogen and other ions on the clay surface likewise were not dominant in the tests using $Ca(OH)_2$ and $Mg(OH)_2$ as the effect might be the same in test using distilled water. Note that also the increasing in molarity from 1mol to 2mol $Ca(OH)_2$ did not produced any improvement in results.

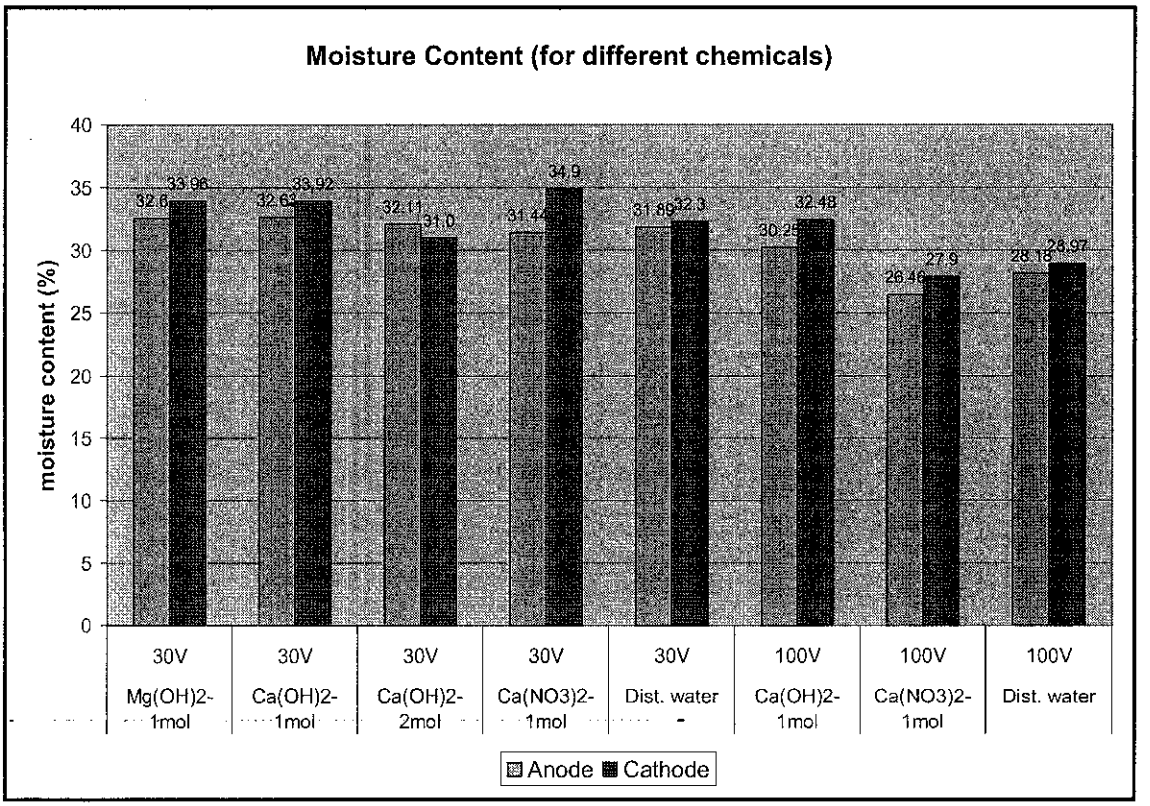


Figure 4.49 Moisture content in samples using $Ca(NO_3)_2$, $Ca(OH)_2$, $Mg(OH)_2$ and distilled water-horizontal cell tests

The variations of current with time were shown in Figures 4.50, 4.51, 4.52, 4.53 and 4.54. Referring to Figure 4.50, it shows 1mol-$Ca(NO_3)_2$-100V and 1mol-$CaCl_2$-100V tests generated high current value of 657 mA and 489 mA, respectively. In all the results obtained especially for tests using $CaCl_2$ and $Ca(NO_3)_2$, the plots generally exhibit

current increase from its initial value and reached a peak, then decreased in an undulating manner or increased again reaching a peak and later decreased again in the same undulating manner. This trend of undulating current is attributed to the very complex behavior and unstable systems in this electrochemical treatment especially in the horizontal cell apparatus set-up. This strange behavior will be discussed further in the upcoming test.

Figure 4.51 shows current results for the various 30V tests with 1mol $CaCl_2$-30V test producing the highest value of 97.2 mA followed by 1mol $Ca(NO_3)_2$-30V producing 74.5 mA. Again both of the results show the same trend of undulating current behavior but not as intense as in the 100V tests.

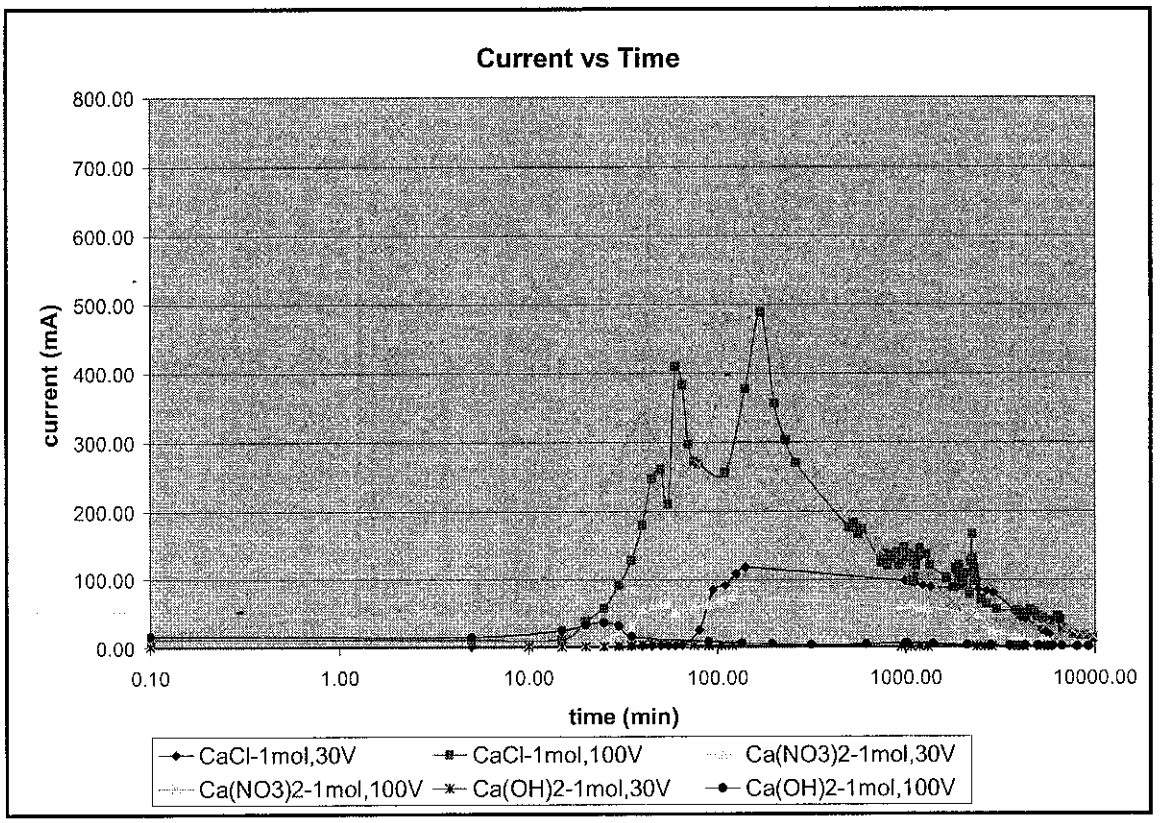


Figure 4.50 Variation of current vs. time-horizontal cell tests-comparion no. 1

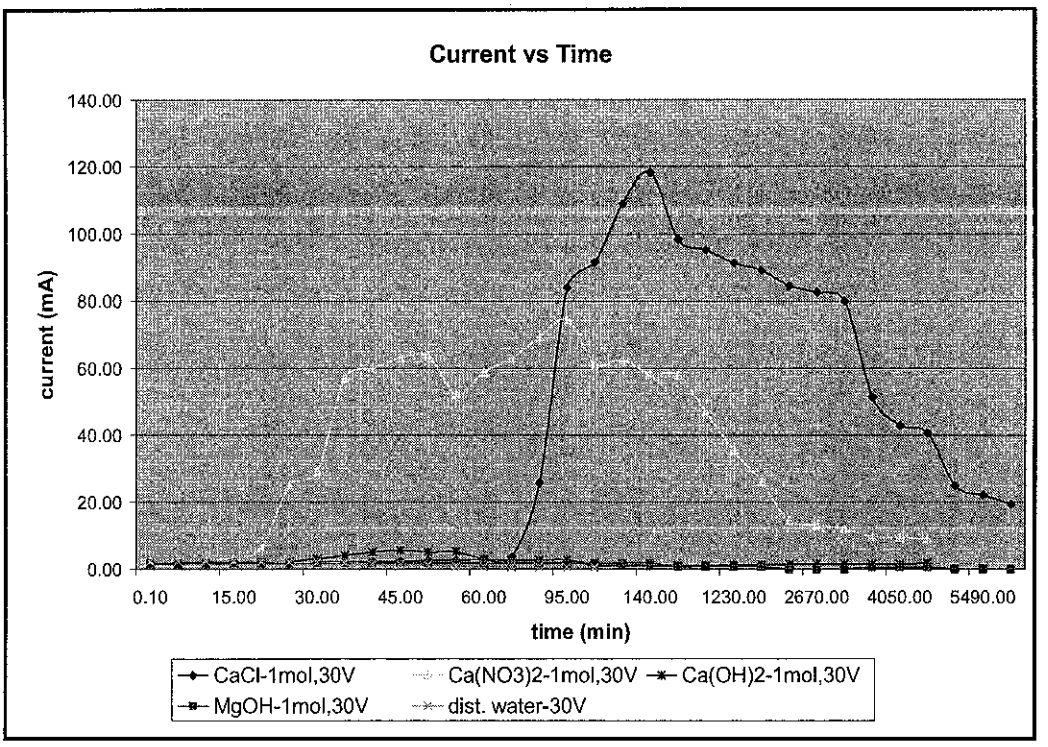


Figure 4.51 Variation of current vs. time-horizontal cell tests-comparison no. 2

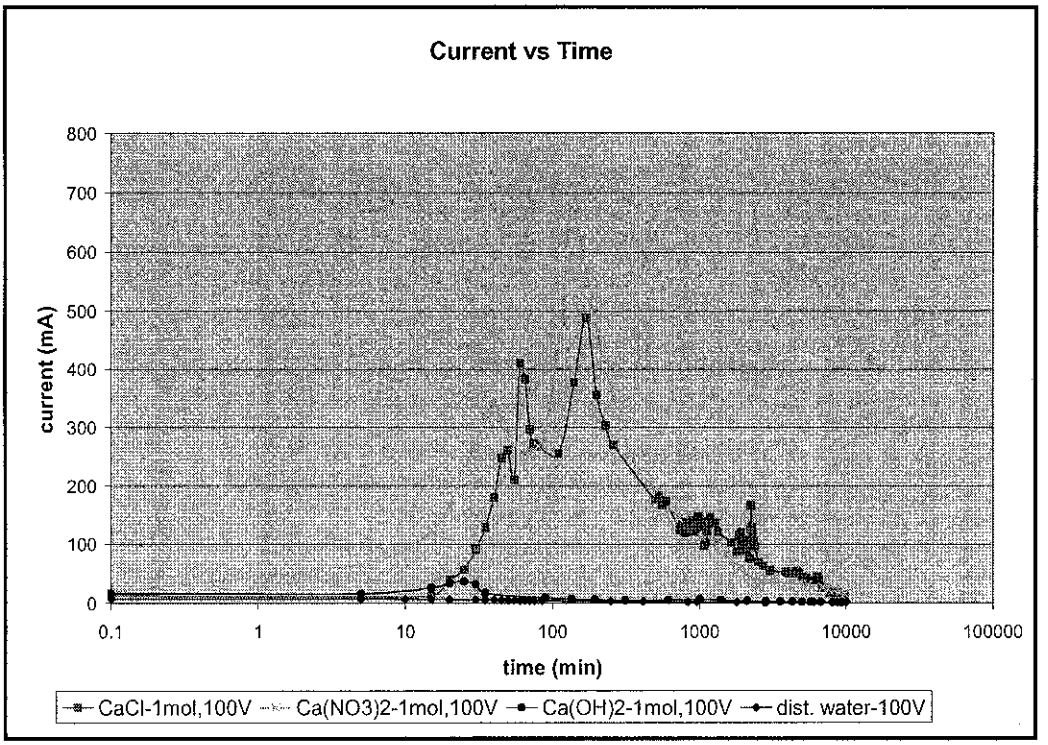


Figure 4.52 Variation of current vs. time-horizontal cell test-comparison no. 3

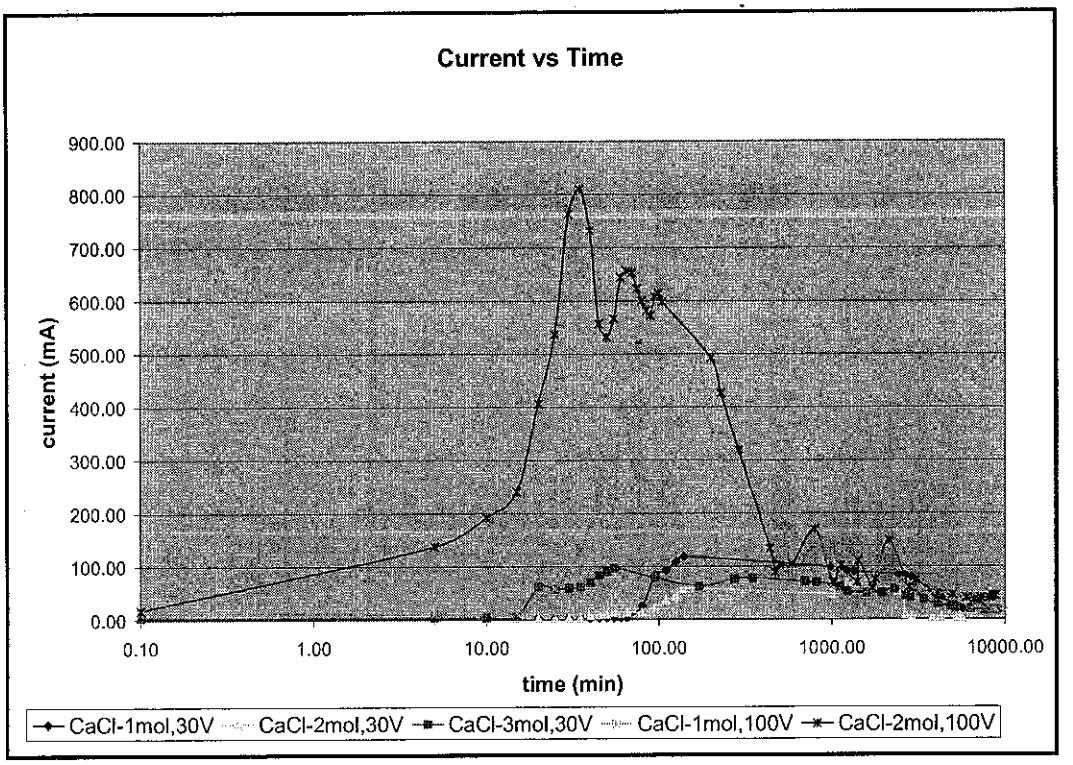


Figure 4.53 Variation of current vs. time-horizontal cell tests-comparison no. 4

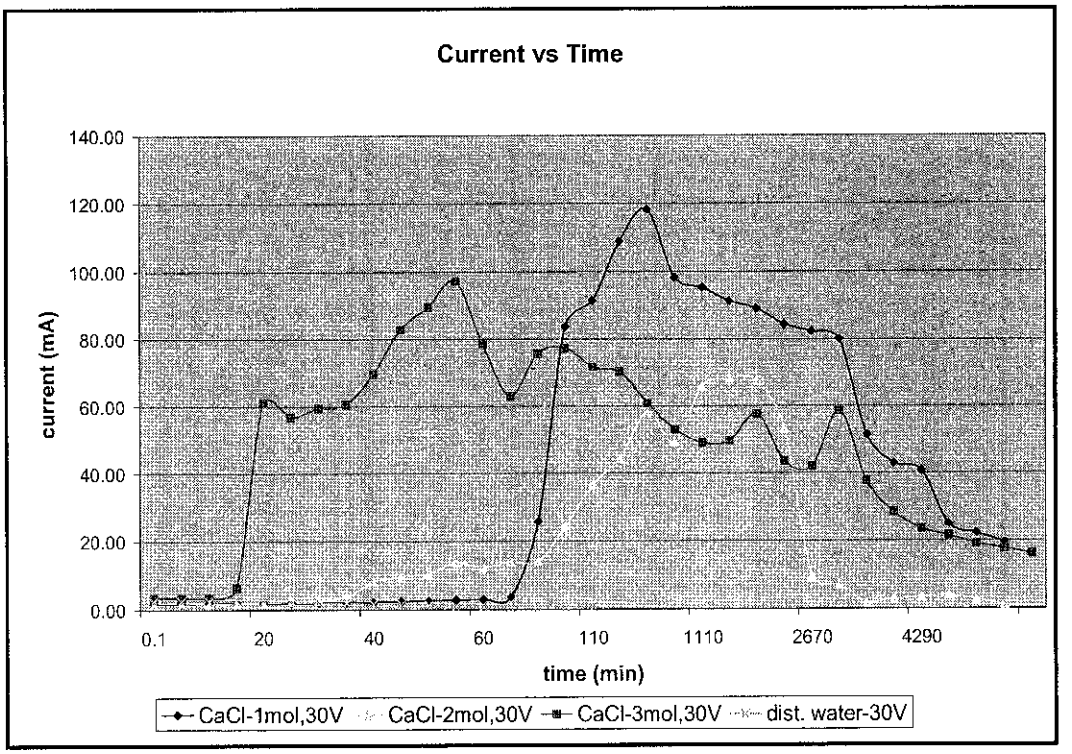


Figure 4.54 Variation of current vs. time-horizontal cell tests-comparison no. 5

Figure 4.54 highlights the results for $CaCl_2$-30V tests using different molarities with the 1mol test giving the highest current value of 118.3 mA, 21 mA more than that which was produced in the 3mol test. The higher current value was a result of higher conductivity in the 1mol test than in the 3mol test due to the reason as explained earlier.

Figure A6, Appendix A shows a picture in the early part of the test where yellow solution was seen to discharge from the discharging tube near the cathode. The yellow discharged solution could be the result of rapid electrode corrosion at the anode containing copper ions. Figure A7 shows the typical water vapour droplets forming at the upper portion of the cylinder when conducting tests using $CaCl_2$-100V and $Ca(NO_3)_2$-100V. In both cases, very high temperature probably close to 90°C or more were felt at the wall of the horizontal cylinder especially at the anode due to the generating of high current density. The high temperature actually caused the perspex cylinder to break and deform permanently in the area close to the anode as shown in Figure A8, Appendix A.

4.3.2 Electrochemical box test – 125 mm electrode spacing

A better simulation of field condition was possible by using the electrochemical box as in the electroosmotic case. A spacing of 125 mm was used to validate the results obtained in the horizontal cylinder apparatus. If approximately the same trend in parameter changes was obtained in this box test, then it could be preliminary concluded that the electrochemical horizontal cell test had provided reliable results at least in the laboratory environment. Only a brief analysis covering this particular set of tests will be given as elaborate analysis will be presented in the box test using 300 mm spacing.

Table 4.14 Results for electrochemical box test – 125 mm spacing

Type of test	$CaCl_2$ 1mol				$Ca(NO_3)_2$ 1mol				$Ca(OH)_2$ 1 mol				$Mg(OH)_2$ 1mol				Distilled Water			
Voltage (V)	30				30				30				30				30			
Surcharge (kPA)	0				0				0				0				0			
Location of sample	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Moisture content (%)	25.2	24.8	25.3	26.2	23.9	23.0	24.3	24.5	25.1	24.8	25.9	24.9	25.3	25.1	25.2	25.5	26.3	26.1	26.0	26.4
Strength (kPA)	18.8	15.2	28.6	2.86	25.7	12.7	24.9	3.68	16.9	8.62	16.9	11.4	18.9	15.4	17.2	16.1	6.76	2.8	2.9	2.75
Maximum current (mA)	234.5				313.15				7.55				3.07				9.53			
Type of test	$CaCl_2$ 1 mol				$Ca(NO_3)_2$ 1mol				$Ca(OH)_2$ 1mol				Distilled Water							
Voltage (V)	100				100				100				100							
Surcharge (kPA)	0				0				0				0							
Location of sample	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4				
Moisture content (%)	10.3	-	-	-	11.9	11.7	12.0	12.2	24.2	24.6	24.9	24.4	22.7	22.6	22.9	22.7				
Strength (kPA)	101	-	-	-	91.0	73.0	90.3	31.2	17.9	19.3	14.7	15.6	25.9	21.5	27.9	6.53				
Maximum current (mA)	1008				815				-				15.63							

Table 4.14 gives results for all the tests conducted. In each test, four samples were taken at four locations as shown in Figure 3.19, Section 3. Locations 1 and 3 were close to the anode and cathode respectively. Location 2 was somewhat in the middle of the 4 electrodes as shown, and location 4 was located somewhere close to the end of the perspex wall situated outside the electrochemical path. Referring to Figure 4.55, test on 1mol $CaCl_2$-100V produced the highest shear strength of 101 kPa followed by test on 1mol $Ca(NO_3)_2$-100V with shear strength of 91.0 kPa. Comparing with the same test using distilled water-100V, the shear strength obtained was only 25.9 kPa. This means that the percentage increase in shear strength for 1mol $CaCl_2$-100V and 1mol $Ca(NO3)_2$-100V tests were approximately 290% and 250%, respectively with the corresponding reduction in moisture content of 55% and 48%, respectively from the values obtained in the electroosmotic test using distilled water-100V. However, if the percentage of reduction in moisture content is compared with the original water content of 50%, percentage reduction was 80% for 1mol $CaCl_2$-100V, 76% for 1mol $Ca(NO_3)_2$-100V, and 55% for the distilled water-100V. Figure 4.56 shows the high reduction of moisture content after electrokinetic processing in both the tests for $CaCl_2$ and $Ca(NO_3)_2$.

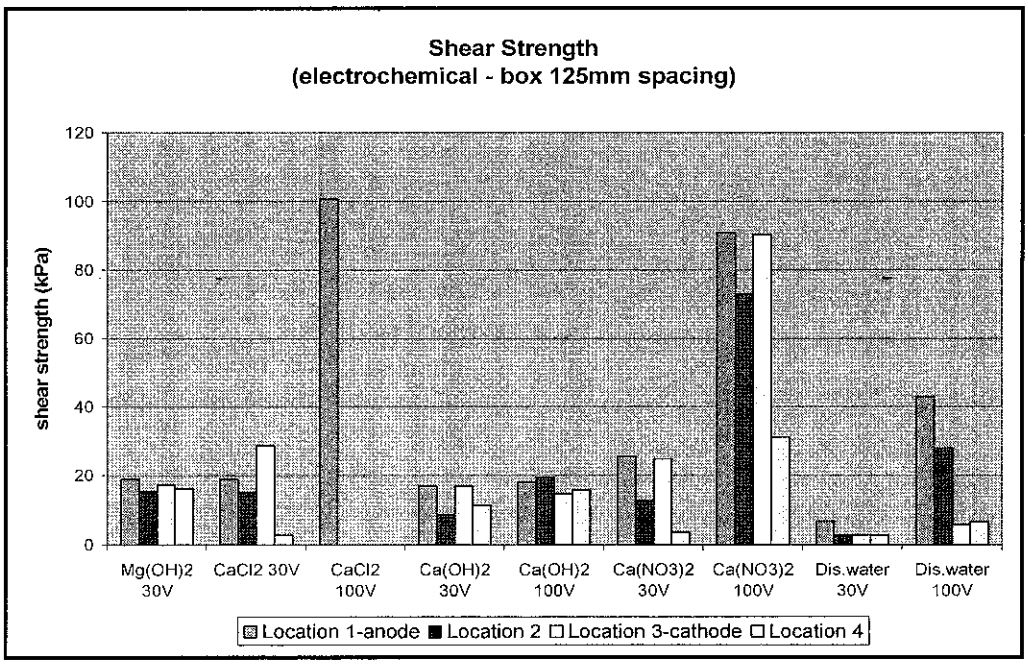


Figure 4.55 Shear strength for electrochemical box test – 125 mm spacing

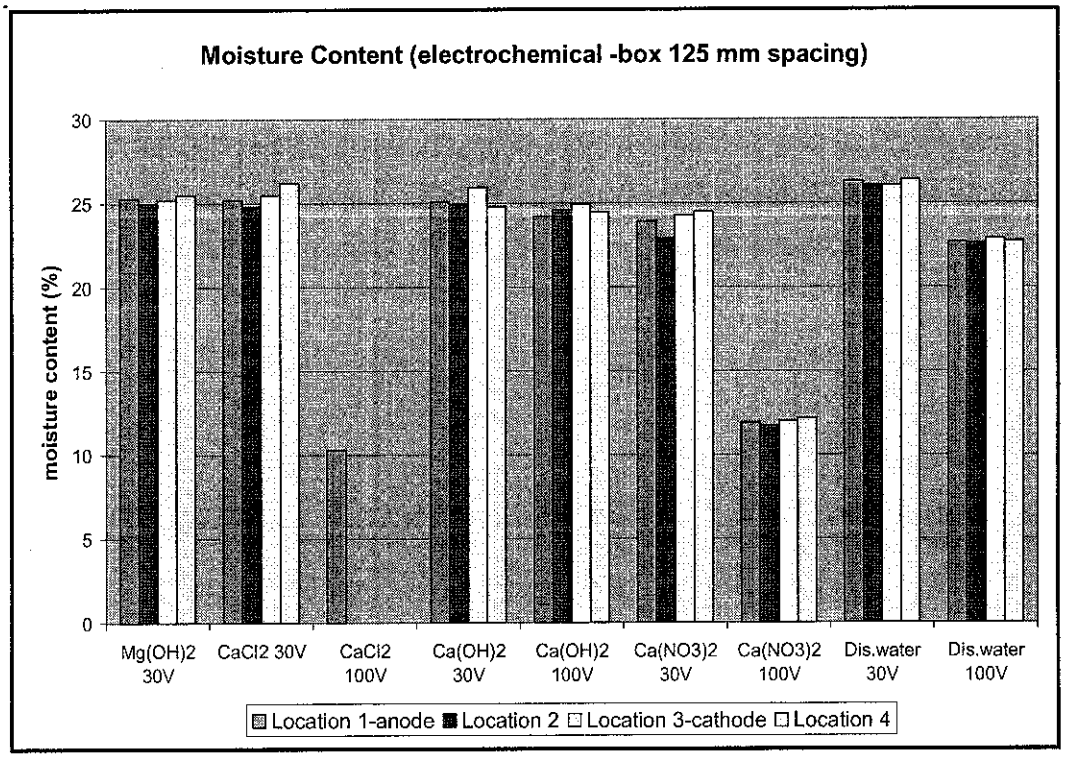


Figure 4.56 Moisture content for electrochemical box test – 125 mm spacing

In general, almost all results show that the highest strength increase were obtained either at cathode or anode, the next highest increase in shear strength was at location 2 and the lowest was at location 4. From Table 4.14, it could be concluded that in all cases, location 4 gave the highest moisture content and the lowest was found ironically in location 2 where the corresponding shear strength was lower than at anode (location 1) and cathode (location 3). Again, because of the short span of test sample, these two locations (location 1 and 3) took turns in exhibiting either a lower value in a particular test and a higher in another in both the shear strength gain and reduction in moisture content. Therefore, in this set of box tests with 125 mm spacing, a clear indication as to whether cathode or anode resulted in better strength gain or better reduction in moisture content could not be determined due to small spacing of electrodes. However, location 2 gave the highest reduction of moisture content but did not produce the highest strength. This gave an early distinct indication of the electrochemical phenomenon which could increase the shear strength even with no change in moisture content. Note that also due to the short

electrode spacing, moisture content for all the four locations in a particular test showed slight variations with significant change in the corresponding shear strength. This again is the nature of electrochemical treatment as oppose to the normal electroosmotic method. The current variations with time are given in Figures 4.57, 4.58, and 4.59. The same trend of increasing current reaching a peak and then reduced in an undulating manner again was observed in tests for 1mol $CaCl_2$-100V and 1mol $Ca(NO_3)_2$-100V. The normal behavior of reduction in current without reaching a peak was observed in the remaining tests given in Figure 4.59. A clear indication of the magnitude of current dictating the corresponding shear strength was also found in this set of experiments when looked into tests using $CaCl_2$-100V, $Ca(NO_3)_2$-100V, $CaCl_2$-30V, and $Ca(NO_3)_2$-30V .

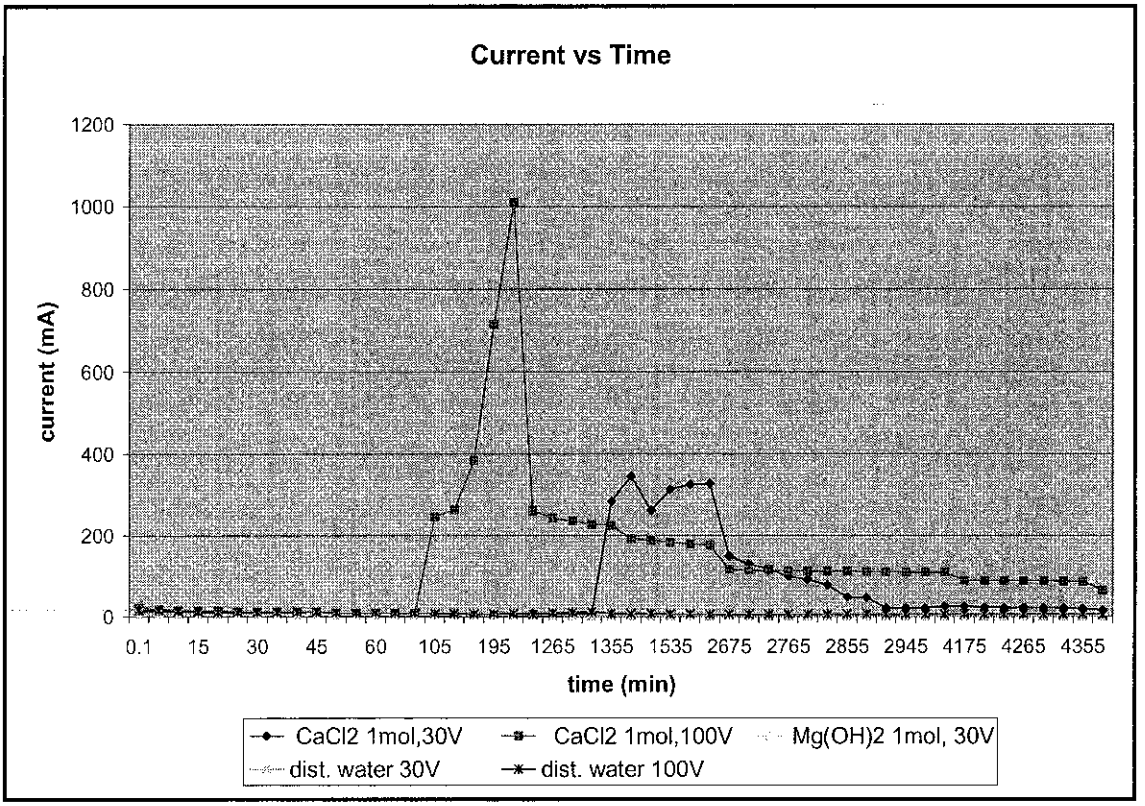


Figure 4.57 Variation of current vs. time-electrochemical box tests-comparison no. 1

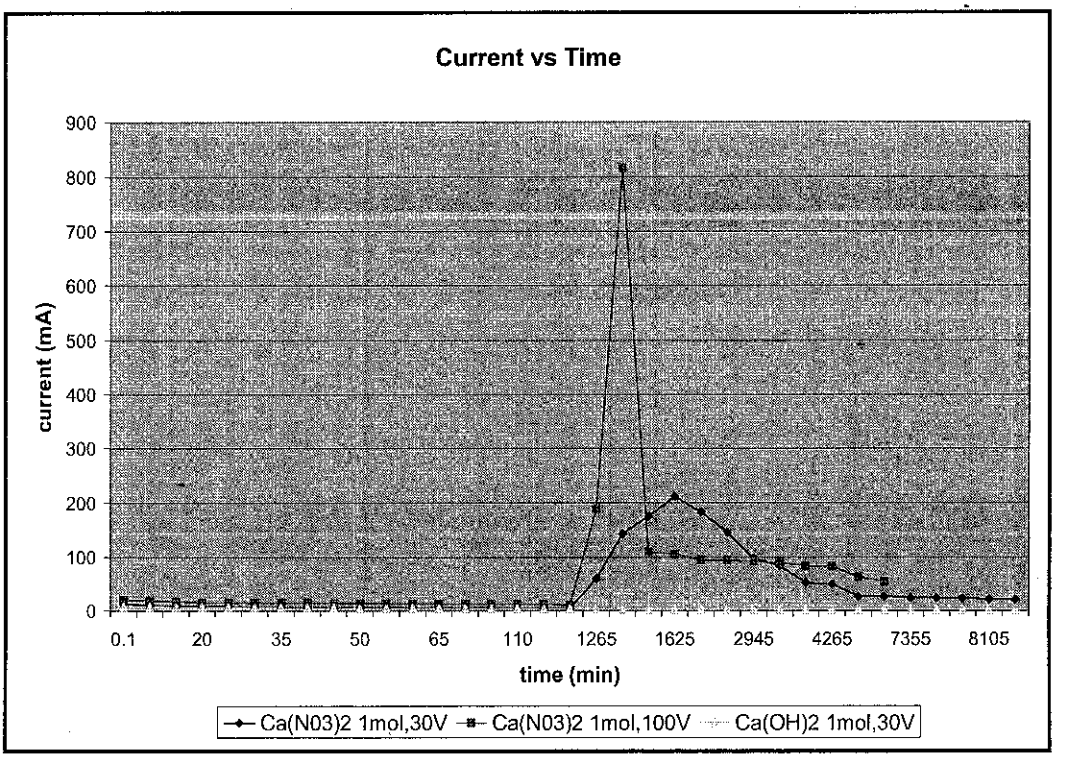


Figure 4.58 Variation of current vs. time-electrochemical box tests-comparison no. 2

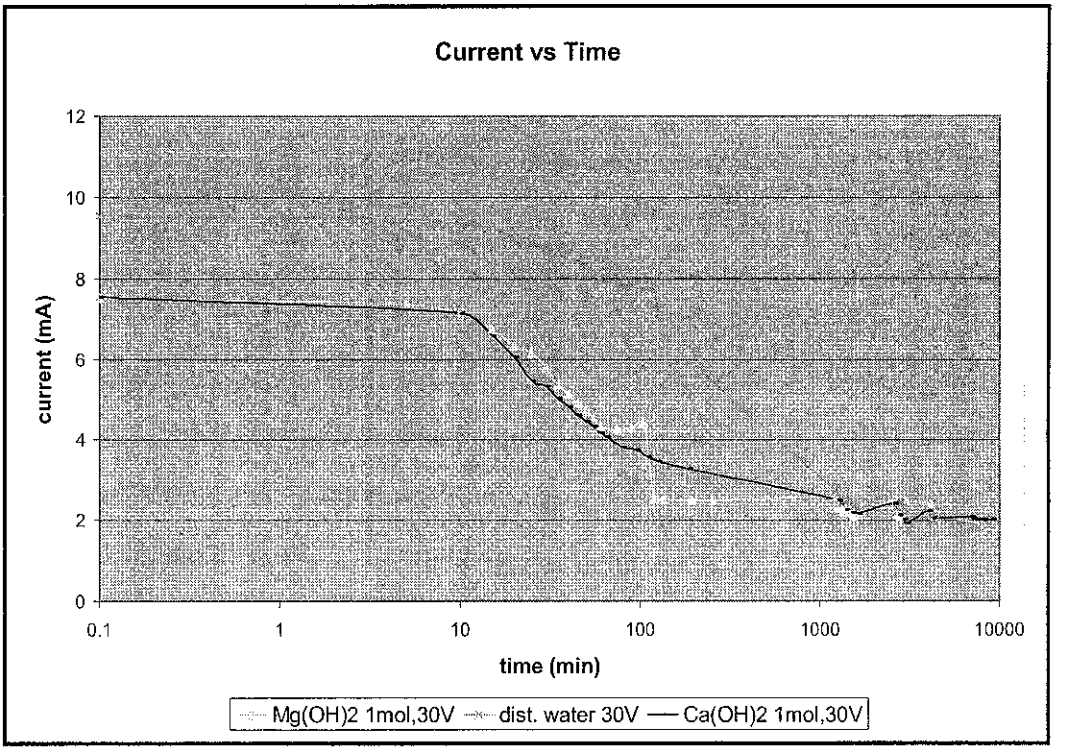


Figure 4.59 Variation of current vs. time-electrochemical box tests-comparison no. 3

In conclusion, comparing the results obtained in the box tests and horizontal cell tests, it could be said that they were not far-off from each other. Figure A9 shows picture depicting high chemical activities in test using 1mol $CaCl_2$-100V as oppose to the test using 1mol $Mg(OH)_2$-100V in Figure A10, Appendix A.

The results of XRF tests for 1mol $Ca(NO_3)_2$-100V comparing with tests using distilled water-100V and untreated sample is given in Table 4.15 and results for 1mol $Mg(OH)_2$-30V comparing with untreated sample is given in Table 4.16 below.

Table 4.15 Percentage contents of compounds in soil sample after treatment-box tests

	Al_2O_3 contents (%)	SiO_2 contents (%)	CaO contents (%)	CuO contents (%)	Fe_2O_3 contents (%)
1mol $Ca(NO_3)_2$-100V (anode)	29.0	61.4	1.59	0.967	0.629
Distilled water-100V	30.5	61.6	0.169	0.0387	0.588
Untreated sample	30.7	61.7	0.158	0	0.772

Table 4.16 Percentage contents of compounds in soil sample after treatment-box tests

	Al_2O_3 contents (%)	SiO_2 contents (%)	CaO contents (%)	CuO contents (%)	Fe_2O_3 contents (%)
1mol $Mg(OH)_2$ -30 V (anode)	31.8	60.9	0.165	0.0314	0.603
1mol $Mg(OH)_2$-30V (cathode)	31.8	60.5	0.168	0	0.659
Untreated sample	30.7	61.7	0.158	0	0.772

Table 4.15 shows that test using $Ca(NO_3)_2$ had higher values of CaO (which is a part of CAH and CSH hydrates) and CuO precipitates, both of which contributed to shear strength increase. Table 4.16 shows 1mol $Mg(OH)_2$-30V at location 1 at anode and location 3 at cathode did not change much except for the presence of CuO at anode which justified the slight variation in shear strength.

SEM photograph for 1mol $Ca(NO_3)_2$-100V and untreated soil are given in Figure A13 and Figure A12, Appendix A respectively. A much more packed and flocculated arrangement are noticed in Figure A13 than in Figure A12 proving the effectiveness of electrochemical treatment using 1mol $Ca(NO_3)_2$-100V.

4.3.3 Electrochemical box test – 150 mm, 300 mm, and 600 mm spacings

This is the final set of extensive experiments conducted in this research which includes using the large box for the 600 mm spacing. A detailed analysis was conducted on the 300 mm spacing test which apart from the normal parameters, variations in pH, voltage, conductivity, and Atterberg limits were also recorded. Results from XRF, X-ray diffraction (XRD), and scanning electron microscope (SEM) tests on the soil samples were also included. Atomic spectrograph (AAS) analysis on the effluent coming out from the cathode side of the sample was conducted with additional tests on pH and conductivity included. For comparing the overall effect of different spacing, supplementary tests were conducted on sample with 150 mm and 600 mm spacings.

Overall results for all the different electrode spacings are given in Table 4.17. The comparison of the shear strength is given in Figure 4.60. It is necessary to mention here that no shear strength value of $CaCl_2$ -100V-150mm test was obtained because in both trials the sample broke during extraction due to its extremely hard nature. Although in Figure 4.60, the test on 300 spacing gives the highest reading at cathode with value of 110.7 kPa, the author believes that the 150 mm spacing would have given a higher strength.

Table 4.17 Results for electrochemical box test – 100 mm, 300 mm & 600 mm electrode spacings

Type of Test	$CaCl_2$ 1 mol		Distilled Water		$CaCl_2$ 1 mol		Distilled Water		$CaCl_2$ 1mol		Distilled Water	
Voltage (V)	100		100		100		100		100		100	
Surcharge (kPa)	0		0		0		0		0		0	
Spacing (mm)	150		150		300		300		600		600	
Moisture content (%)	Ano.	Cat.	Ano.	Cat.	Ano.	Cat.	Ano.	Cat.	Ano.	Cat.	Ano.	Cat.
	10.34	10.32	23.26	25.34	18.8	22.48	28.5	29.73	31.22	32.1	35.3	34.1
Strength (kPa)	-	-	29.82	30.46	64.0	110.7	28.6	28.6	4.16	90.3	3.6	12.0
Max. current (mA)	1060		16.7		659.2		5.01		507		2.62	

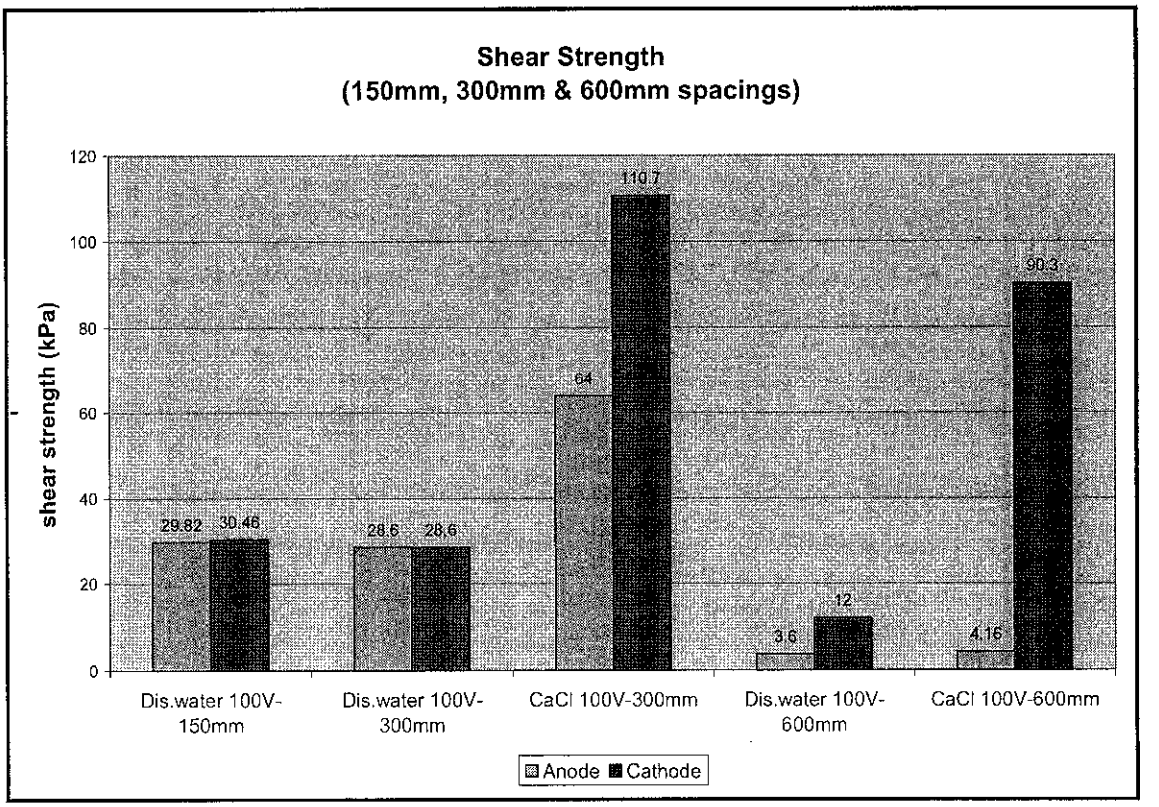


Figure 4.60 Shear strength gain in 150 mm, 300mm and 600 mm spacings

A clear distinction of values in shear strength between cathode and anode could be distinguished for both 300 mm and 600 mm spacing in electrochemical test where a bigger spacing gave bigger difference. This behavior was not found in the electroosmotic tests using distilled water. There was a very big difference in strength between the two electrodes in $CaCl_2$-100V-600mm spacing which shows that the strength gain at anode was just about the same as in the electroosmotic test at anode. To further examine the strength gain at different locations for $CaCl_2$-100V-600mm spacing test, Figure 4.61 is given. It shows that for this spacing, the big increase in shear strength was located close to the cathode (approximately within 75 cm in the vicinity of the the cathode) while the rest of the locations basically exhibit approximately the same shear strength. Surprisingly, although the magnitude of shear strength gain at anode was not large in the electroosmotic test 100V-600mm, the same trend of having larger strength at cathode persisted.

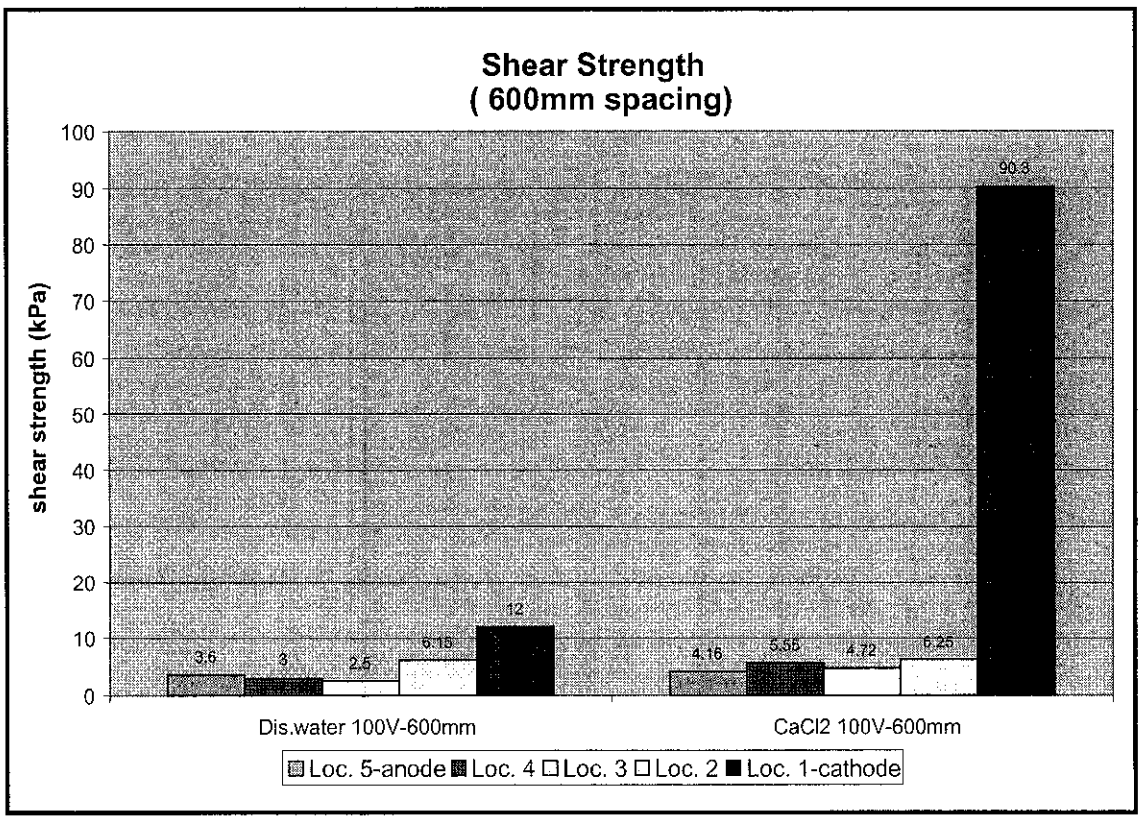


Figure 4.61 Shear strength variations along sample for 600 mm spacing

Figure 4.62 and 4.63 give the results on the corresponding moisture content. Concentrating on $CaCl_2$-100V-600mm and $CaCl_2$-100V-300mm spacing, the final moisture content at cathodes for both the tests were larger than in anodes. Both show the same trend of having higher moisture content at cathode but with a higher gain in shear strength. This proved that the enhancement came from the effect of ionic migration from electrochemical process which took place within the system and not much from the electroosmotic process. This is in line with the fact that there are several different chemical, electrical and electrochemical processes that become active within the soil-liquid medium when a soil is subjected to electrochemical processing. These processes change the system chemistry and collectively affect the soil micro-structure, consequently modifying many soil properties (Jayasekara, 2007).

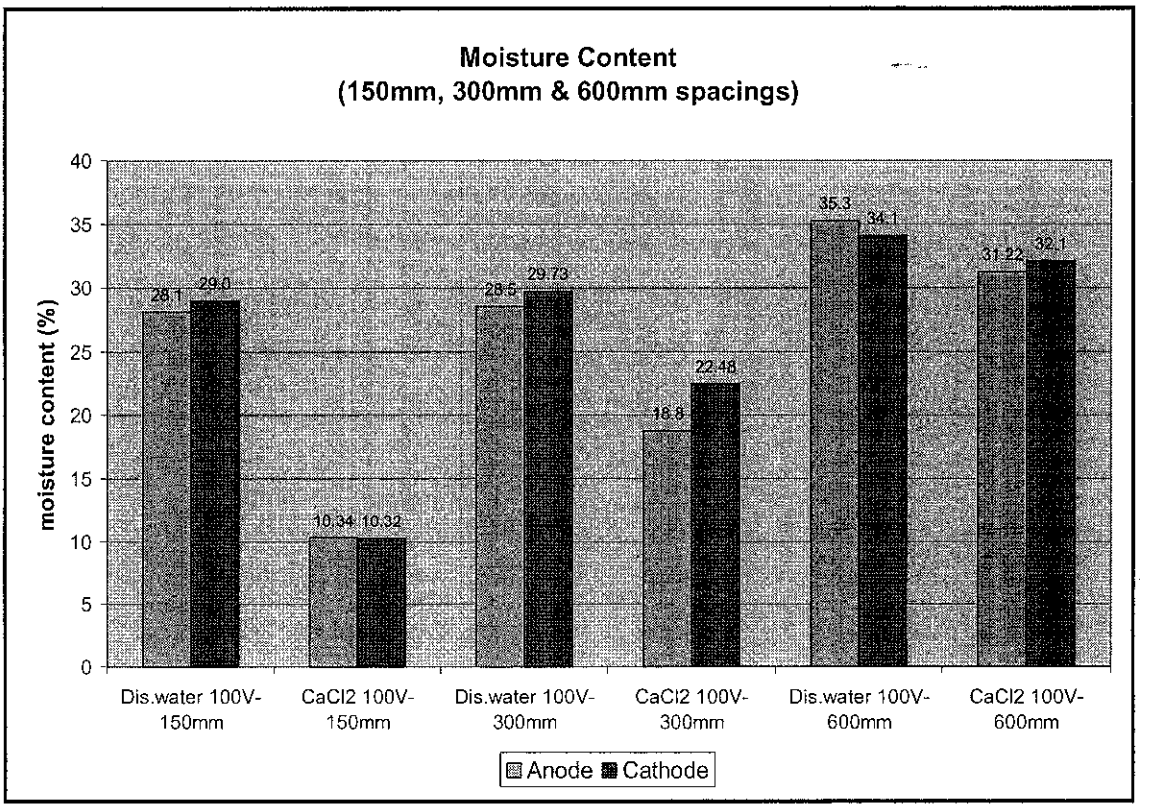


Figure 4.62 Moisture content in 150 mm, 300 mm and 600 mm spacings

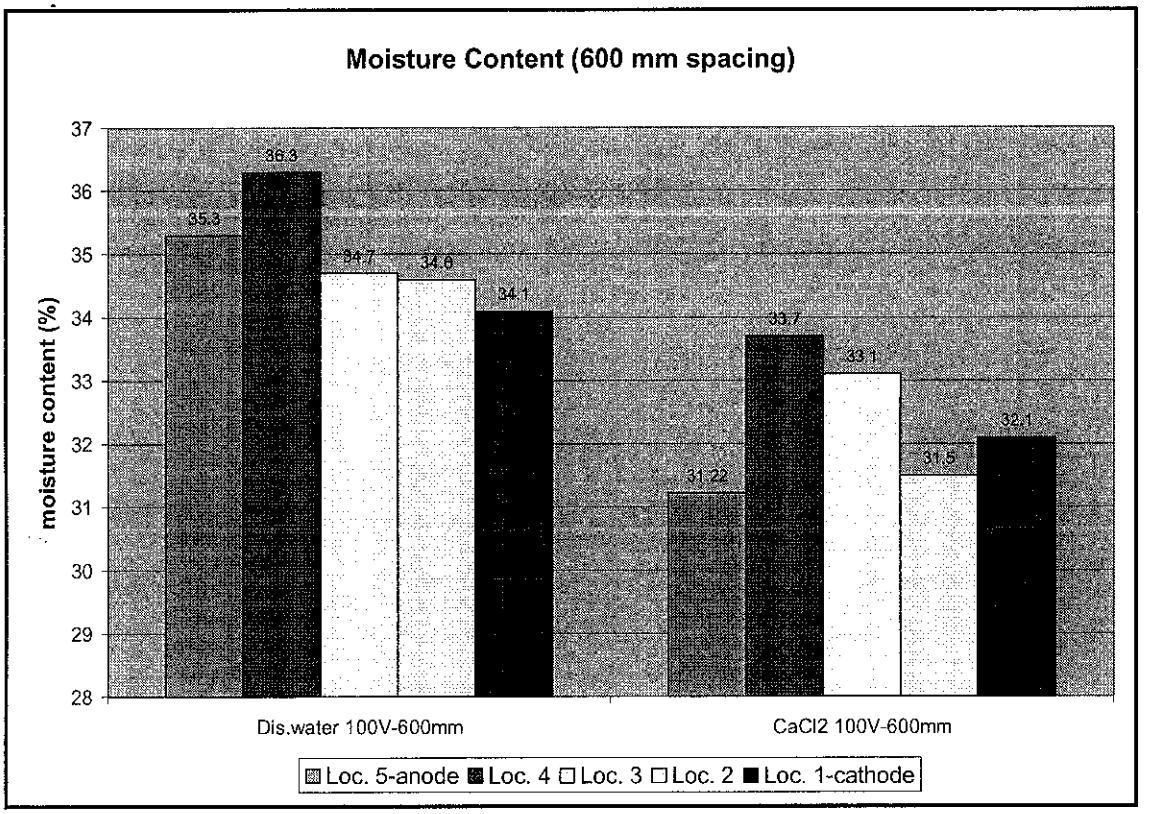


Figure 4.63 Moisture content in 600 mm spacing

The important difference between both methods was that, the mode of chemical transport in electrochemical treatment can potentially occur even without any fluid flow as oppose to electroosmotic method which rely on the presence of water to induce chemical transport (Gray and Mitchell, 1967). The same effect was obtained by Alshawabkeh and Sheahan (2004) in their laboratory electrochemical treatment on Boston Blue Clay using phosphoric acid. High strength was gained near the cathodes but at the same time the moisture content throughout the soil sample was even more than the initial 49% water content which confirmed the shear strength increase was not related to soil consolidation which is a consequence of electroosmotic process. Generally, in the normal electroosmotic test, location near anodes will exhibit better enhancement of properties than at cathodes including strength gain due to higher negative pore pressure and better cation replacement leading to change of Atterberg Limits. As reduction of pH in the anode progresses, aluminium ions from the clay structure replaces free hydrogen ions on

the clay surface, resulting in a flocculated, more stable structure. In addition, low pH value causes an increase in edge-to-edge contacts especially in kaolinite soil (Thomas and Lentz, 1990). This was proven in this research by referring to Table 4.11 where by using steel electrodes, the performance at anode were better than that in cathode. However, this should not be taken as a rule of thumb because in many previous researches, depending on the soil type, type of electrodes and other factors, the enhancement at cathode were better than that of anode. Tests using distilled water in the 300 mm and 600 mm spacing and also the 200 mm spacing in slope condition (Table 4.20) all proved that soil near cathode experienced better strength enhancement and better reduction in moisture content. This shows that when using copper electrodes, better precipitation and cementation effect could have occurred at cathode due to its high pH environment.

The behavior of current variation in Figures 4.64 and 4.65 expressed that closer spacing generated higher current value. Again, the same trend of current increased to a peak value and then reduced in an undulating manner prevailed in the $CaCl_2$-100V test. As mentioned previously the undulating current was due to the variations in conductivity/resistivity which was probably due to the predominant acidic environment in the soil system causing ionization of kaolinite, dissolved precipitates, desorbed surface cation species; all these activities increased conductivity. However, when reaching the vicinity of the cathode, the ions started to precipitate and hence increasing resistivity (current reduced). Somehow, within the same time, again the acid front would dissolve the precipitates formed near the cathode and caused increased in conductivity. This cycle would prevailed after a certain period of time especially within the first 48 hours or so and then the intensity of this process would reduce gradually until it stabilized towards the end of the test period. Ozkan et al. (1999), confirmed the fact that acidic soil condition causes ionization of kaolinite, dissolves basic precipitates, desorbs surface cation species into the pore fluid, and lead to a flocculated soil structure.

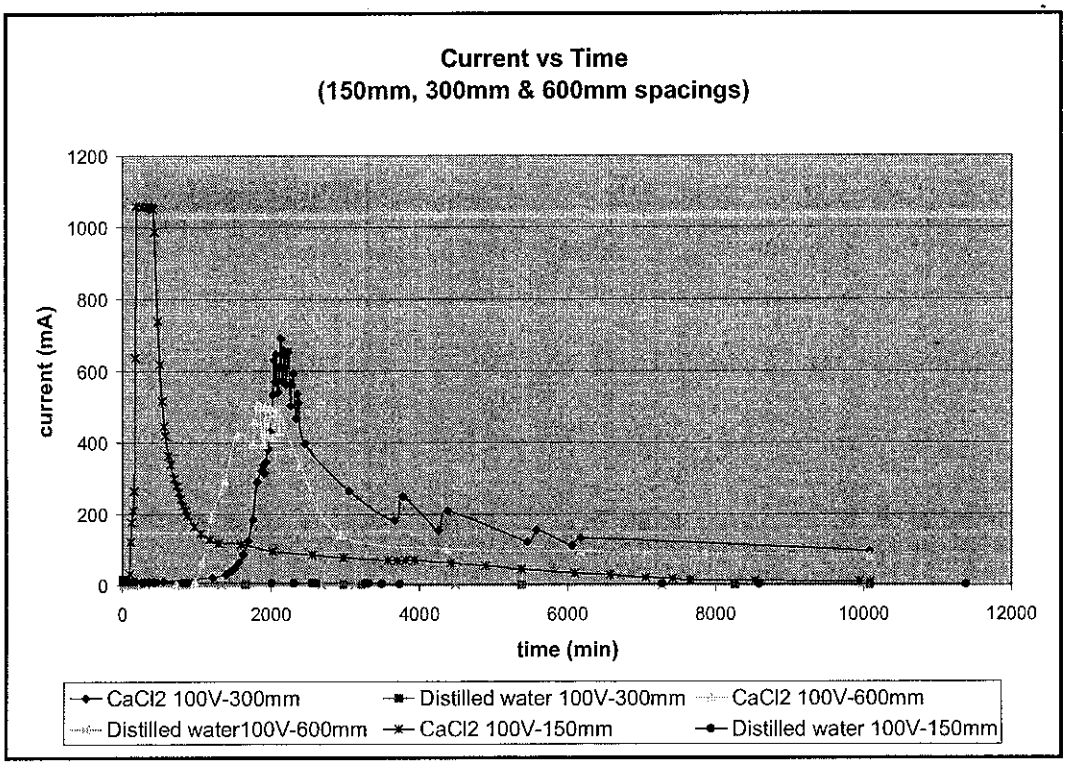


Figure 4.64 Variation of current with time for 150mm, 300mm and 600mm spacings

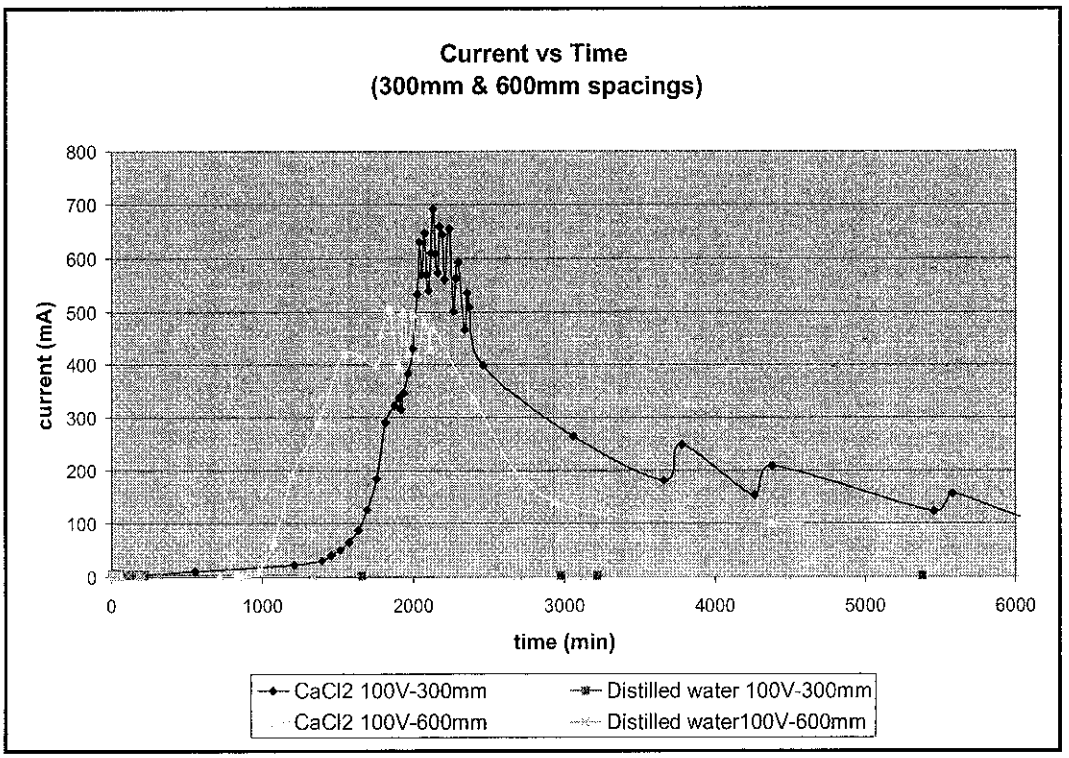


Figure 4.65 Variation of current with time for 300mm and 600 mm spacings

The nature of increase in resistivity within the vicinity of the cathode which caused current reduction towards the end of the test could be understood more by referring to Figures 4.66 to 4.71.

Figure 4.66 shows the variation of voltage at different intervals during the test for 1mol $CaCl_2$-100V using 300 mm spacing. By analizing Figure 4.66, initially the system shows a very high linear voltage gradient throughout the span of the specimen indicating that conductivity was low since ionization activities was low. Current variation in Figure 4.65 shows that at time zero and early part of the same test, current value was low indicating low conductivity. Alshawabkeh & Sheahan (2003) noted that, a linear voltage distribution should occur across the treated soil specimen if the electrical conductivity is uniform in the soil between the electrodes and this was the case initially at the beginning of the treatment (at time zero).

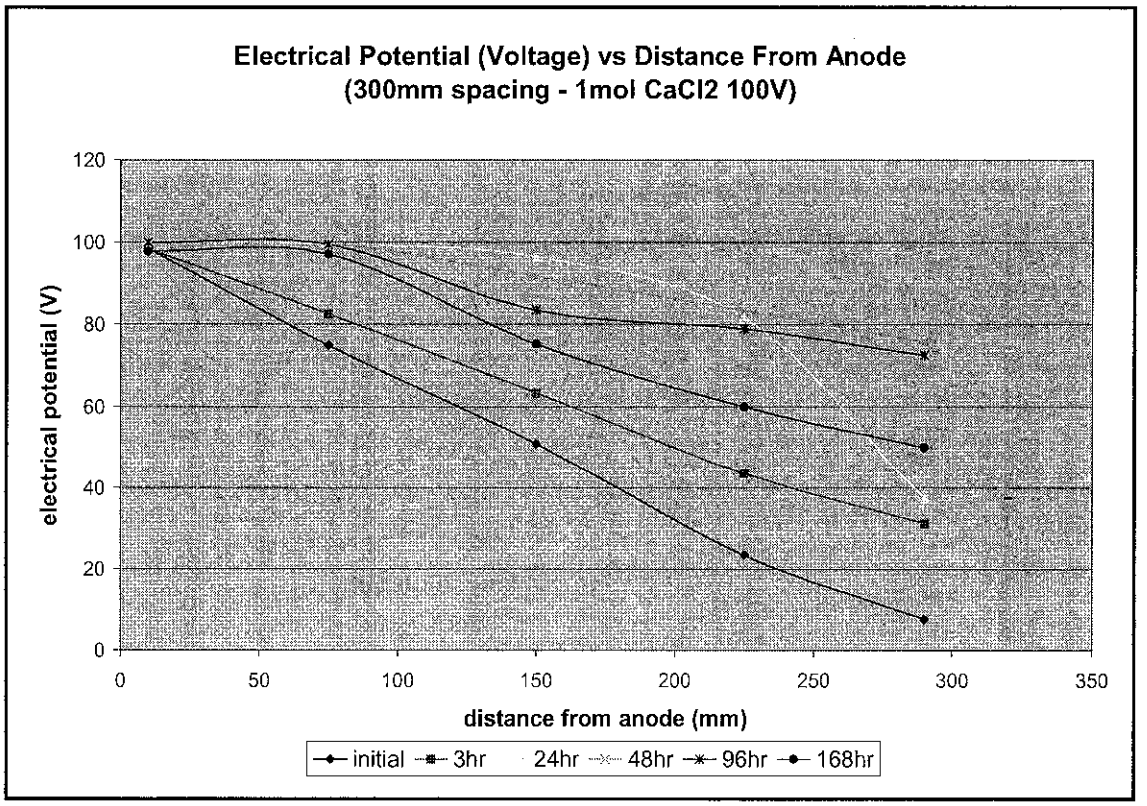


Figure 4.66 Variation of voltage from anode to cathode for 300 mm spacing-$CaCl_2$

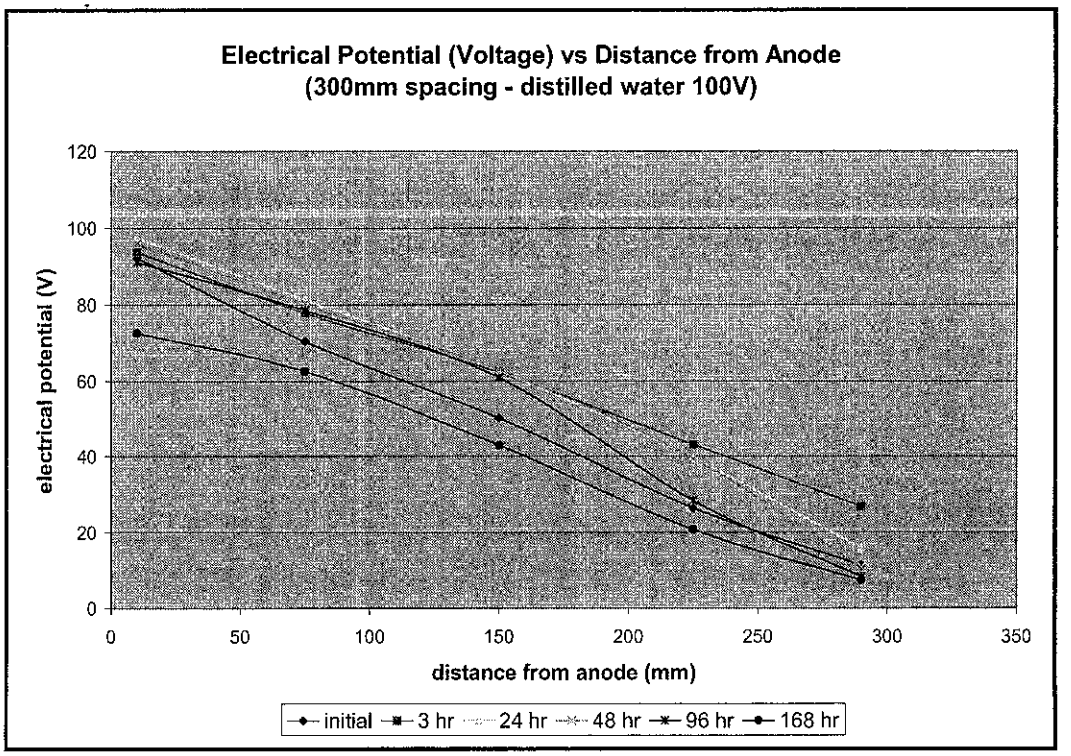


Figure 4.67 Variation of voltage from anode to cathode for 300 mm spacing-d.water

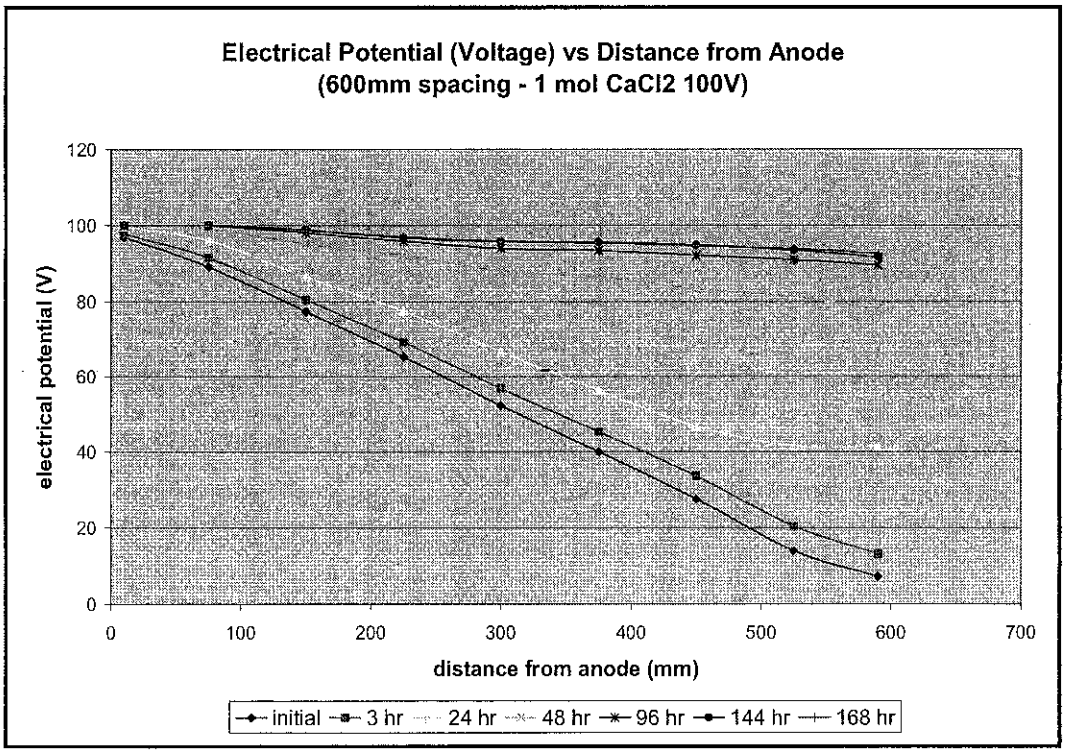


Figure 4.68 Variation of voltage from anode to cathode for 600 mm spacing-$CaCl_2$

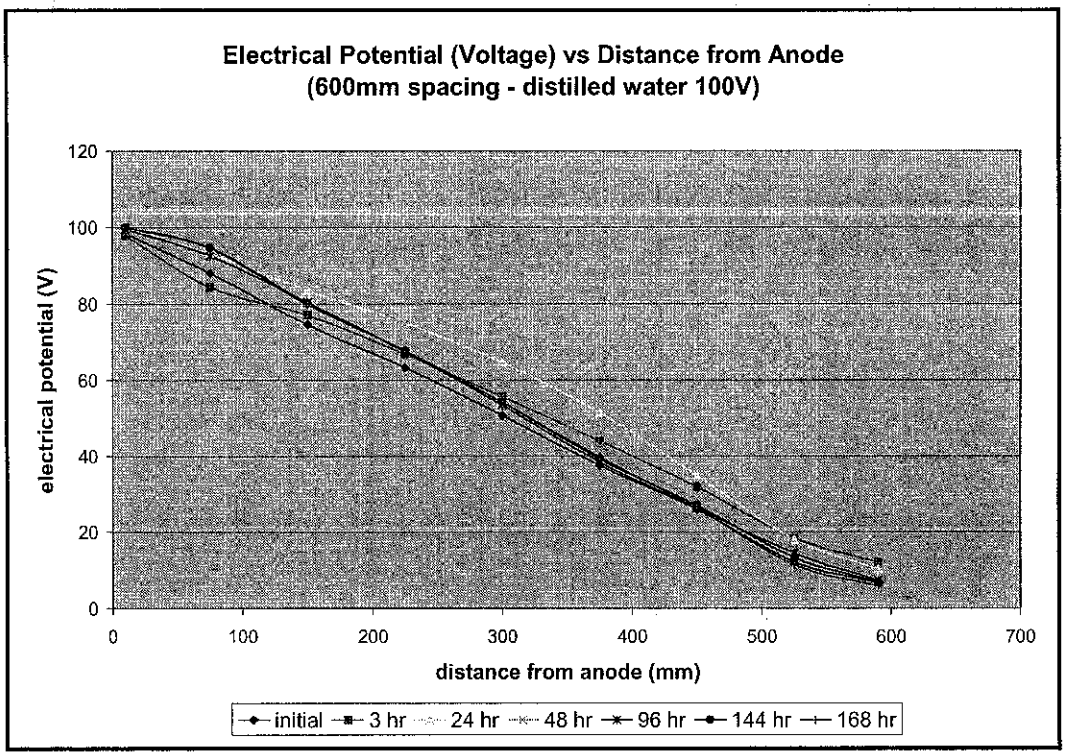


Figure 4.69 Variation of voltage from anode to cathode for 600 mm spacing-d.water

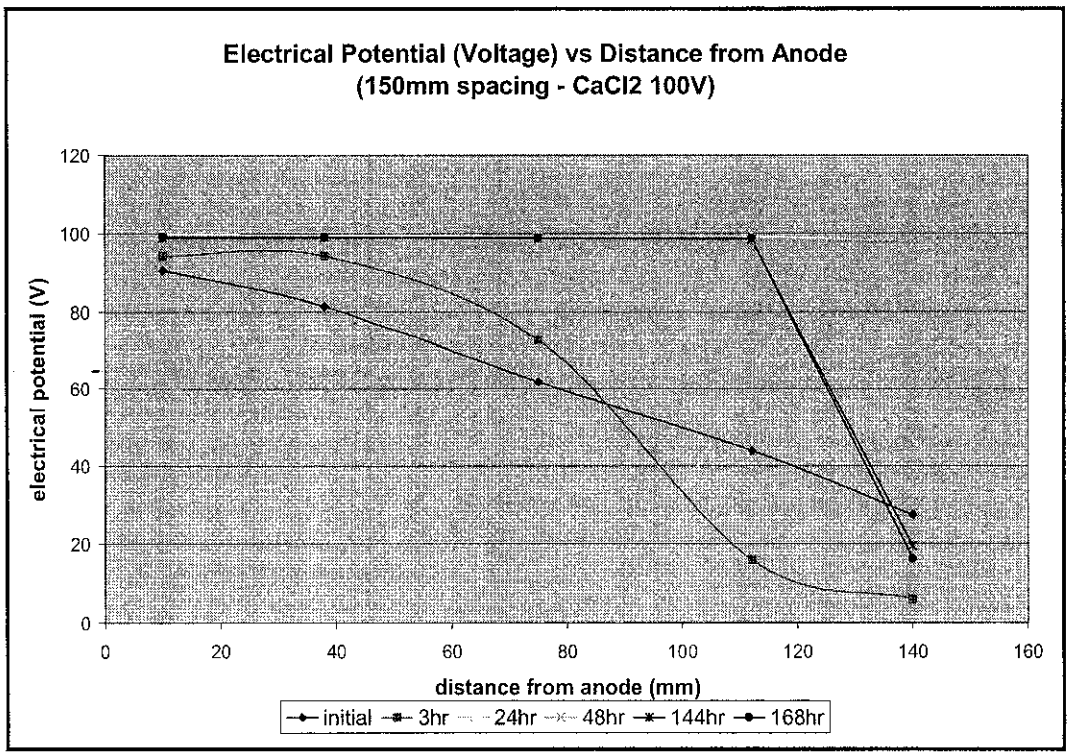


Figure 4.70 Variation of voltage from anode to cathode for 150 mm spacing-$CaCl_2$

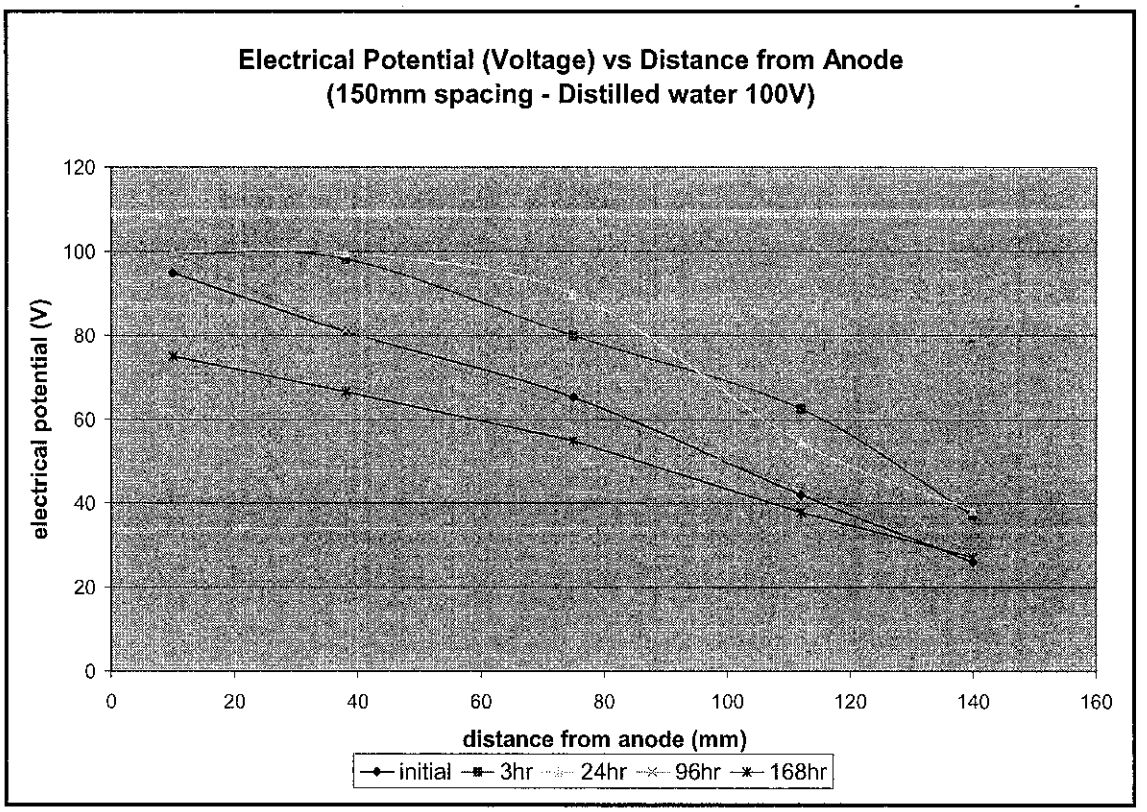


Figure 4.71 Variation of voltage from anode to cathode for 150 mm spacing-d.water

Note that in the same Figure 4.66 at point 290 mm from anode, the voltage drop for the initial period from point 290 mm to point 300 mm (location of cathode) was slightly higher than that of 0-290 mm due probably to the initial contact resistance at the interface between the soil and cathode. This contact resistance existed because of the method of placing electrode at the location of cathode during setting up. The same behavior was noticed in the plot for 3 hr except that the voltage drop/gradient along location 0-290 mm was lower showing a higher conductivity due to ionization activities. At point 290-300 mm, the drop was about 31.2V. This significant drop of voltage at the vicinity of the cathode indicated formation of a high resistivity zone.

The formation of high resistivity in the vicinity of the cathode mentioned above especially at a higher period of time was due to several reasons;

i. Change to a higher pH value due to the production of OH^- ion at cathode. High pH value resulted in the gradual dissolution of alumina and silica around the

cathode which reacted with Ca^{2+} ions possibly forming CAH and CSH compounds as mentioned before. Figure 4.72 proved this concept by observing the high alkaline condition at the cathode.

ii. Formation of precipitates of hydroxides or oxides which was triggered or supported by the high alkaline environment.

iii. Acid front and base front met and formed neutralized zone close to the cathode although the author feels that if this neutralized zone would to happen, the location would somewhat be a little bit further away from the cathode.

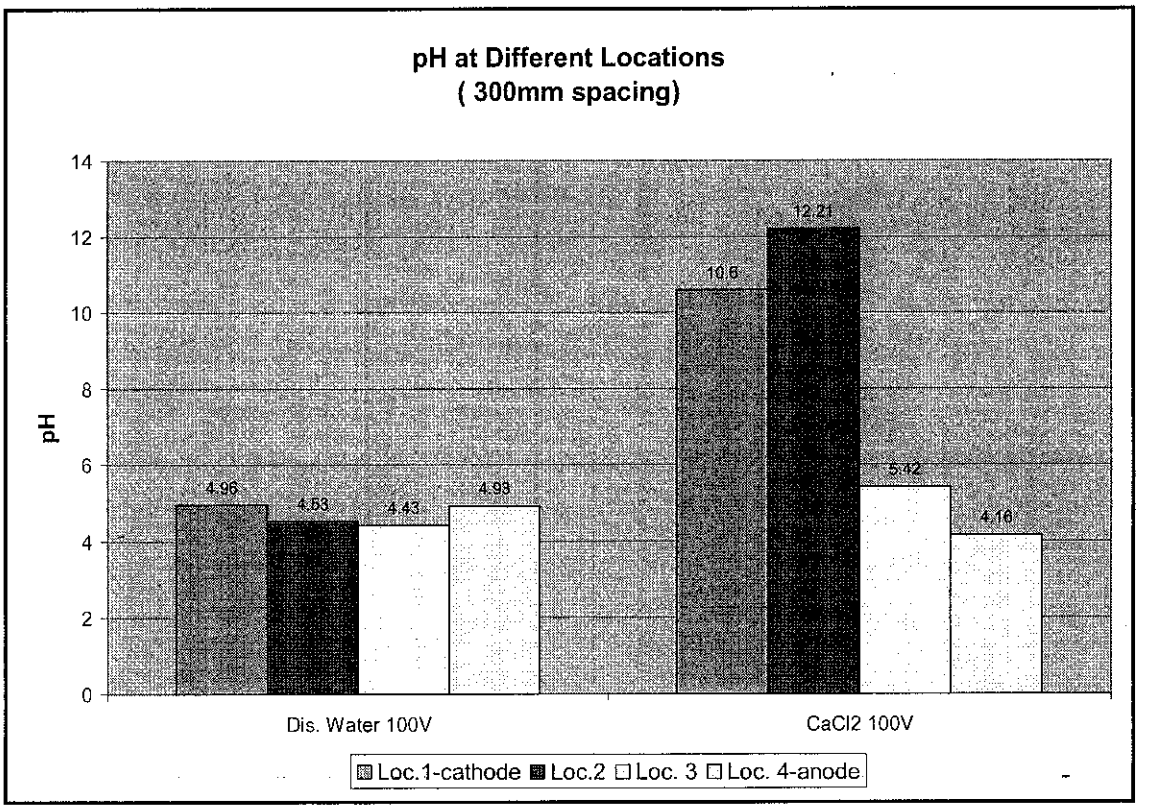


Figure 4.72 Variation of pH at different location between electrodes

In the case for plot 24 hr in the same Figure 4.66, a sudden decrease in the voltage gradient and hence increase in conductivity between 0-220 mm could be explained by referring again at Figures 4.64 and 4.65. At 24 hr (1440 min), the plot for test using 300 mm spacing show the current value began to increase indicating an increase in conductivity. Voltage gradient at point 220-300 mm increased indicating high resistivity

due to high precipitation and cementation effect. The 48 hr plot shows a very uniform and lower voltage gradient at 0-290 mm and shows maximum voltage drop (max. resistivity) from point 290-300 mm. An interesting phenomena is shown for the 96 hr and 168 hr plot where the voltage drop at 290-300 mm began to decrease exhibiting a decrease in resistivity probably due to increase in ionization activities.

Esrig (1967) conducted electrochemical treatment using calcium chloride injected at cathode on illitic soil and observed that the pH value at cathode increased rapidly within a few hours resulting in the rapid increase in Atterberg limits at the cathode. He concluded that the electrochemical hardening at the cathode was due to the increase in Atterberg limit as a consequence of ion exchange. Investigation revealed that there was no evidence of precipitation and cementation effect. However, in the opinion of the author, in the case of this particular electrochemical tests conducted on kaolinite soil in this research, ion exchange or increase in cation exchange capacity did not play an important role in the overall stabilization. This was because of several reasons;

i. Kaolinite soil has a very low CEC value (about 3-15 meq/100g). The nature of exchangeable cation does not make much difference in kaolinitic clay but it can have significant effect in clay soils containing montmorillonite (Bell, 1996).

ii. Referring to Figures 4.73, 4.74, and 4.75, it could be concluded that there were changes in Atterberg Limit in both the tests using distilled water and $CaCl_2$, but the change did not result in significant stabilizing effect in $CaCl_2$.

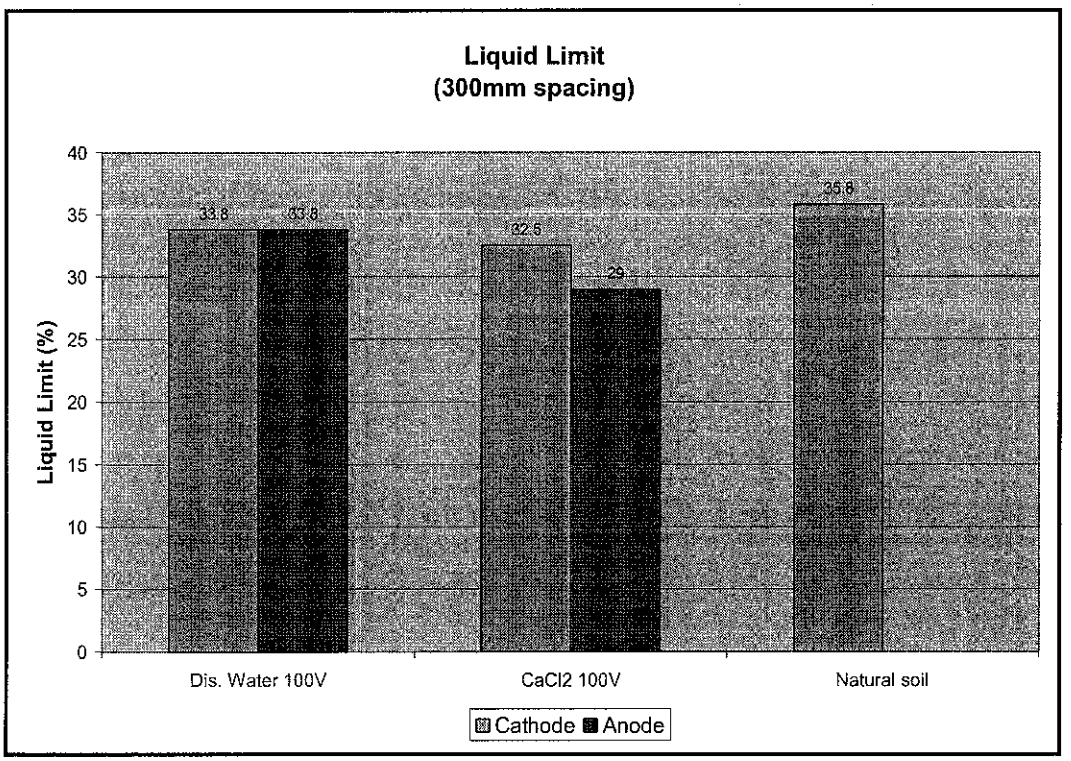


Figure 4.73 Changes in liquid limit after treatment

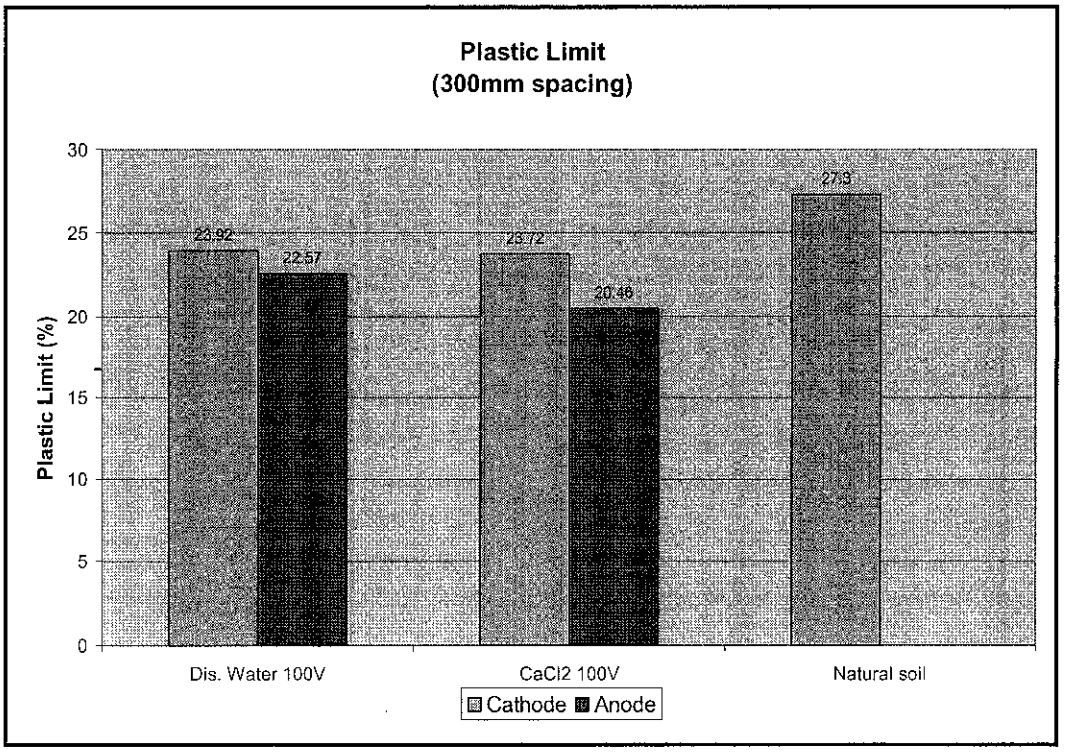


Figure 4.74 Changes in plastic limit after treatment

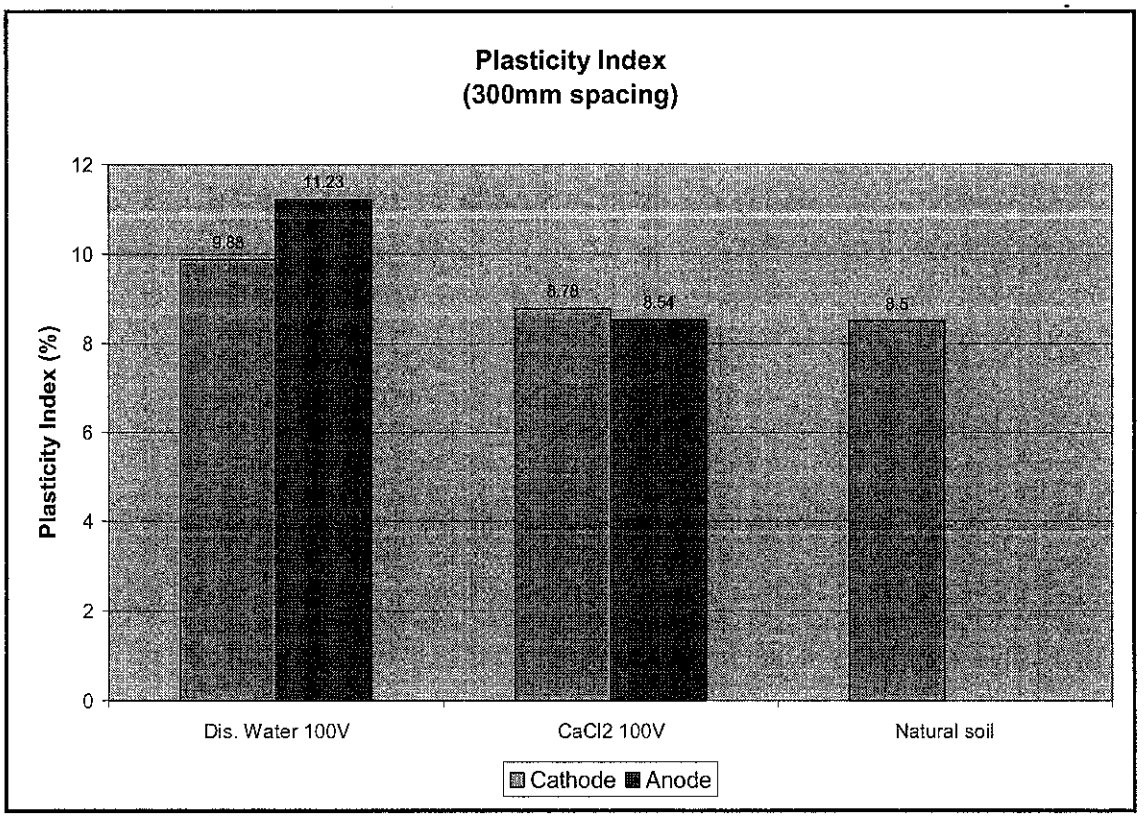


Figure 4.75 Changes in plasticity index after treatment

Comparing the value of untreated natural soil, significant changes in LL and PL were detected in tests using $CaCl_2$ especially at the anode. These changes indicated ions exchange had taken place regardless of the low CEC value of koalinite soil. One would expect that increasing the LL of a soil at a particular moisture content could increase its strength, and as a consequence, decrease its compressibility under a particular increment of stress (Esrig, 1967). Also in general, the desired changes in Atterberg limits would be the reduction in the PI which is normally the result of increase in PL and reduction in LL. This reduction in PI applies in many types of soil when treated with chemical such as lime in the conventional lime treatment and also in electrochemical method. However, many tests had shown that at times, the PI for kaolinite clay soils increased after treatment. Bergado (1996) reported that increase in PL can be associated with the effect of flocculation and coagulation of soils into larger size particles. It should be emphasized that in many cases, the results of cation exchange (without ion migration) affects more on

the modification aspect of the soil and not much of stabilization which means that flocculation results in changes in the soil workability, permeability, plasticity, swell properties and perhaps a relatively small increase in strength.

Referring again to Figures 4.73, 4.74, and 4.75, the tests using $CaCl_2$ and distilled water reduced both LL and PL values indicating that the desire change in Atterberg limits as stated above was not achieved through the ion exchange activities. However when referring to Figure 4.75, the value of PI changes significantly for electroosmotic test using distilled water and change minimally for test using $CaCl_2$. The maximum changes of PI comparing with untreated soil for test with $CaCl_2$ was 3.2% at the cathode and for distilled water was 32.1% at the anode. A very important conclusion which could be derived from the change in PI was that the author's hypothesis of ion exchange did not play a significant role in this electrochemical treatment was validated by the small change in PI. On the other hand, the significant increase in PI for tests using distilled water demonstrated that the enhancement in soil properties was largely contributed by the modification process and the strength increase was largely due to consolidation in electroosmotic process and small stabilizing effect due to small physico-chemical changes in soil. This was validated by a report from Bjerrum (1967) who stated that in one of the field tests conducted, the marked increase in the plasticity index could be ascribed to a real change in the clay fabric caused by the passage of the electric current.

The variation of voltage at different location along the sample for electroosmotic test-100V using distilled water is given in Figure 4.67. The plottings for all period of treatment show an approximate linear voltage distribution occurred across the treated soil specimen demonstrating uniform electric conductivity in the soil between the electrodes from point 0-290 mm from anode. As conductivity is dependant on zeta potential, the value of k_e was assumed to be constant during the electroosmotic process so long as there was no change in the concentration of ions or pH of the pore fluid. At point 290 mm from anode (close to the cathode) the voltage drop to about 15V for the initial period (zero time) again indicated contact resistance between the soil and anode. A higher voltage drop experienced by the 3 hr period shows a high resistivity zone probably due to precipitation or formation of CuO in an alkaline environment near the cathode. Figures

4.76 and 4.77 shows the presence of CuO at the cathode for this particular electroosmotic test.

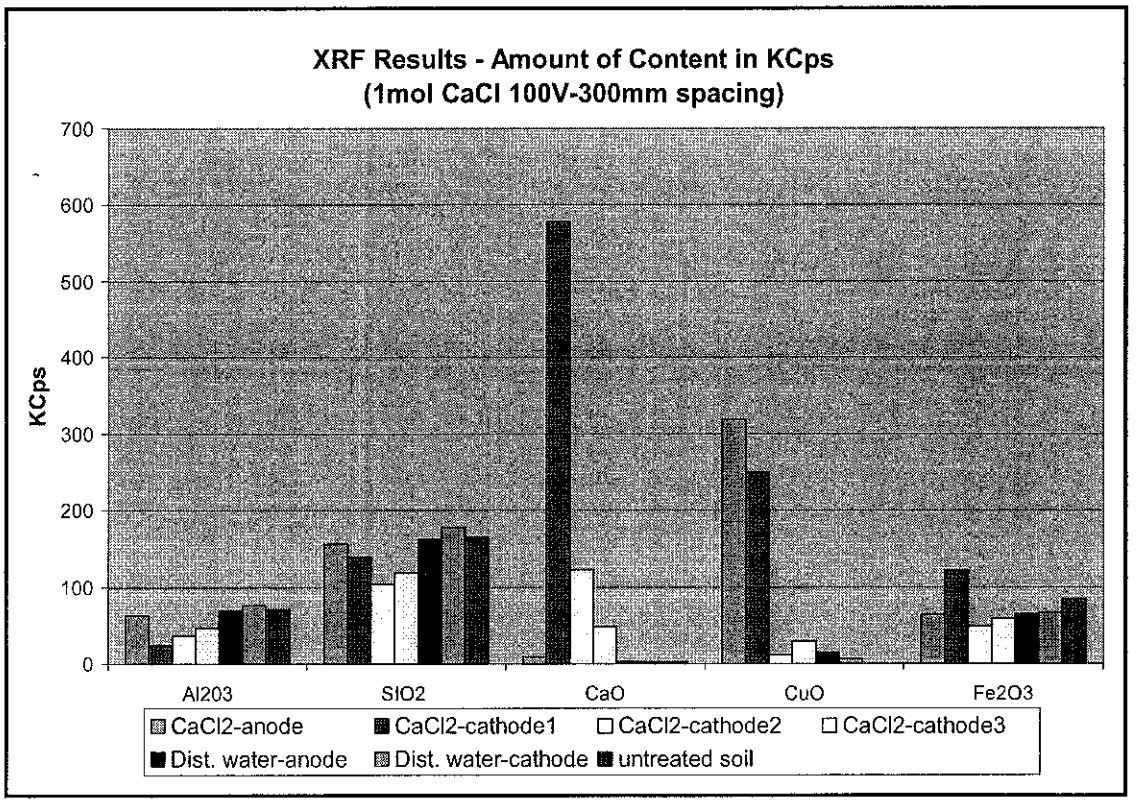


Figure 4.76 XRF results – amount of contents in KCps

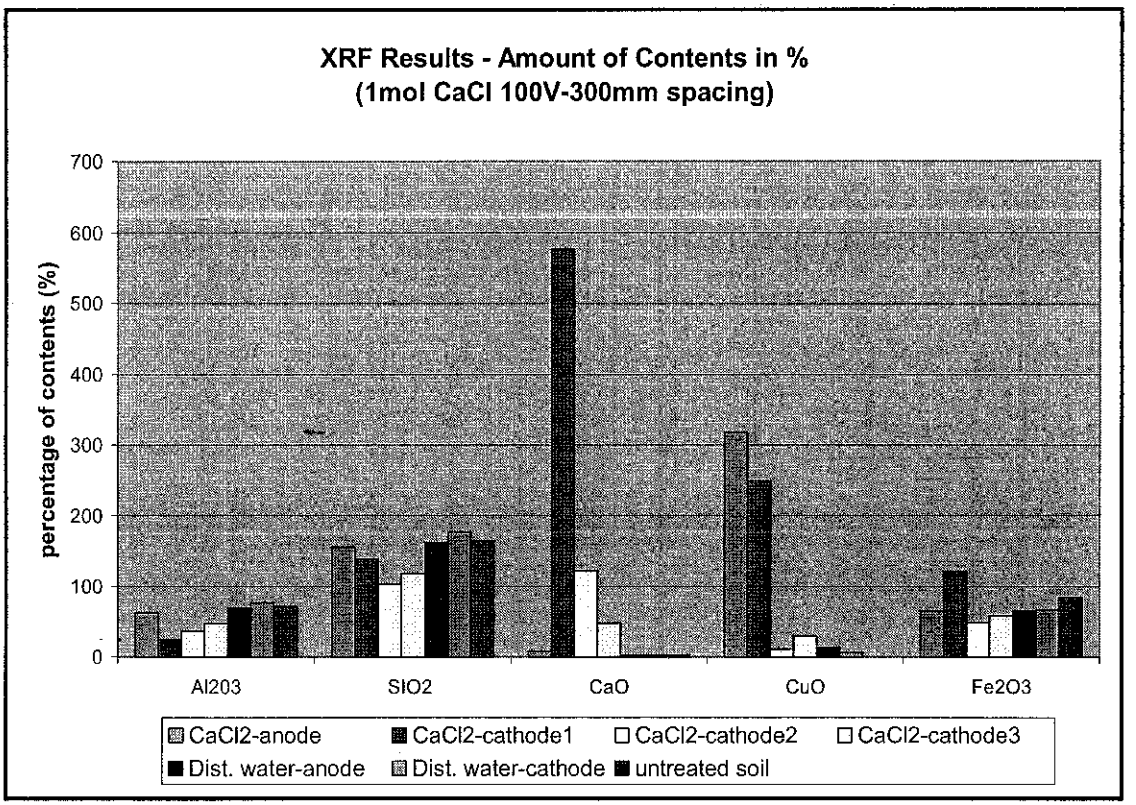


Figure 4.77 XRF results – amount of contents in percent

For the subsequent period of treatment (24, 48, 96, and 168 hr) given in Figure 4.67, the voltage drop at the cathode decreased indicating decrease in resistivity due to dissolve of precipitates and ionization activities. This ionization activities was brought about by the acid front moved forward towards the cathode and could be confirmed by referring to Figure 4.78 which shows that the pH value at both the anode and cathode at the end of test period were in the acidic region (pH=4.93 and 4.98 respectively). In Figure 4.67, the plot for 168 hr shows that there was a much bigger voltage drop at the anode than the rest of test periods. The voltage drop from point 0-10 mm was 27.5V and from 290-300 mm was only 7.3V. This shows that at the end of the test period, the resistance at anode was higher than that of cathode which was not found in the electrochemical treatment as was in the case of the test using $CaCl_2$ of the same 300 mm spacing.

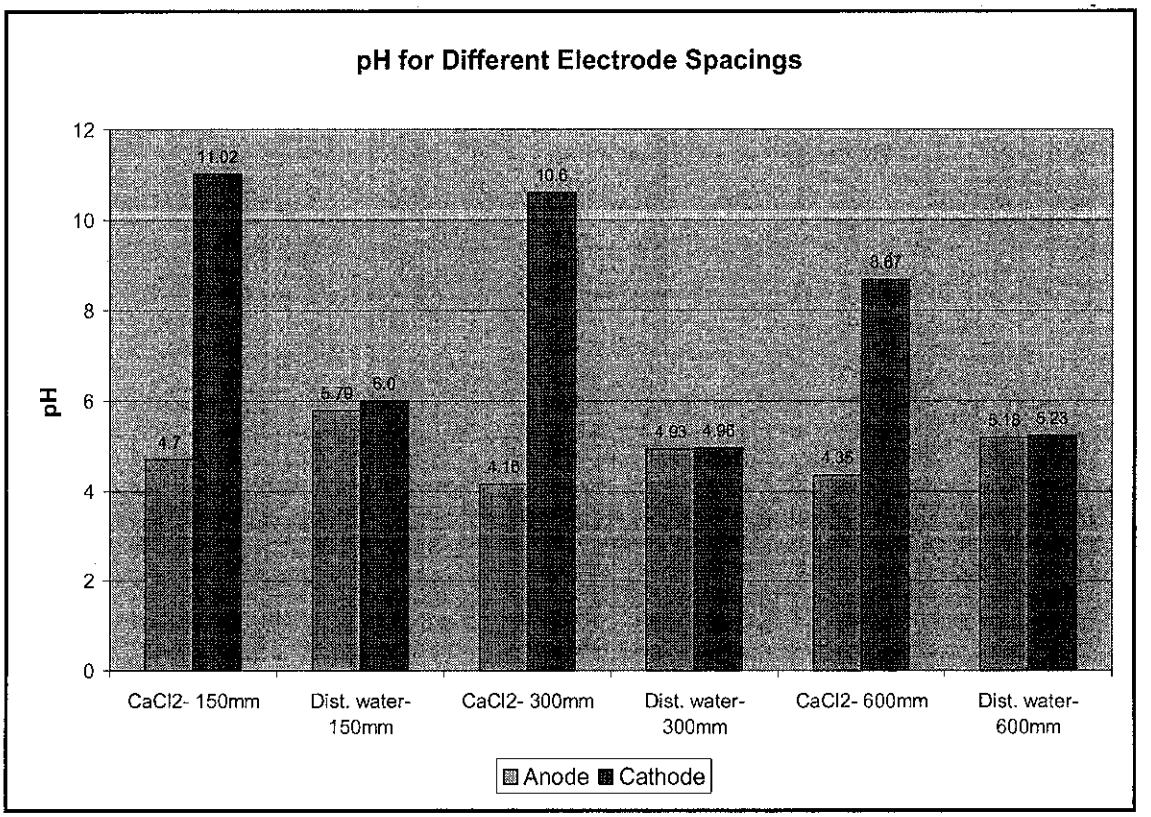


Figure 4.78 pH value for different electrode spacings

Figure 4.79 proved the above point by showing the conductivity at anode was 18 μS and at cathode was 47 μS in the distilled water case as oppose to >5000 μS at anode and 118 μS at cathode in the test using $CaCl_2$-300mm spacing. A better distribution of conductivity in the 300 mm spacing, both for $CaCl_2$ and distilled water tests are given in Figure 4.80. The increase in resistivity or decrease in conductivity at anode in test using distilled water was due to the increase in precipitation of CuO formed at the anode as could be seen in Figure 4.76 and Table 4.18 where the values of CuO at the anode and cathode were 14.5 kCps and 6.4 kCps, respectively.

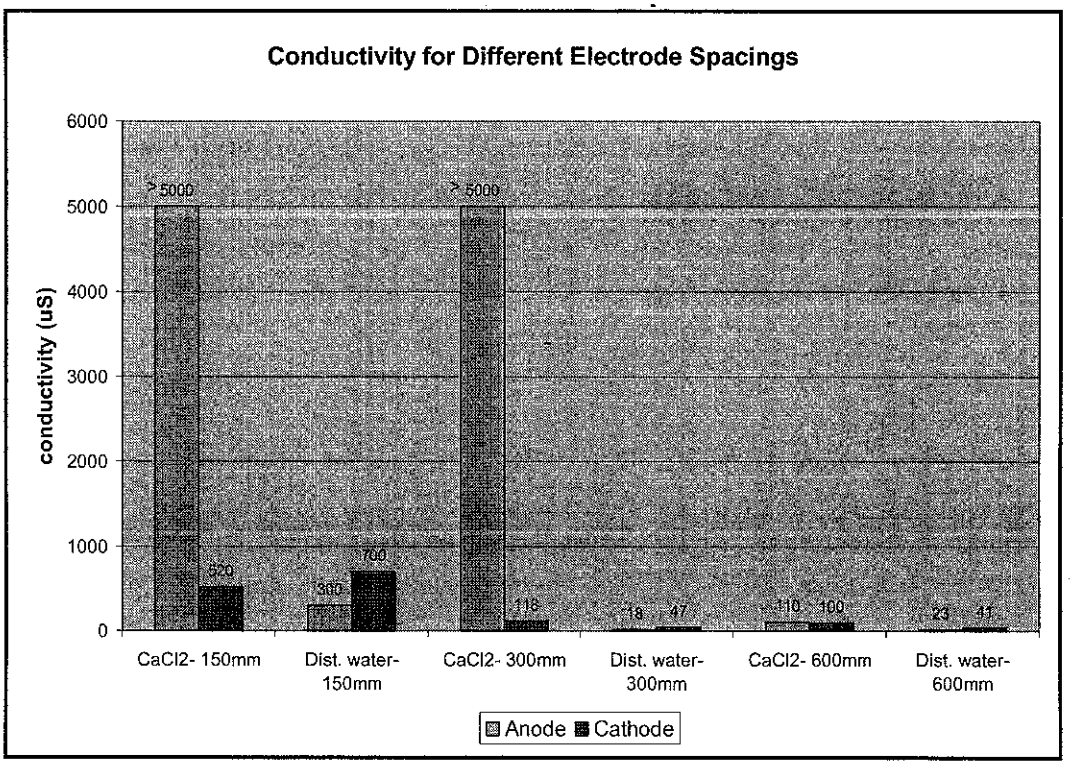


Figure 4.79 Conductivity value for different electrode spacings

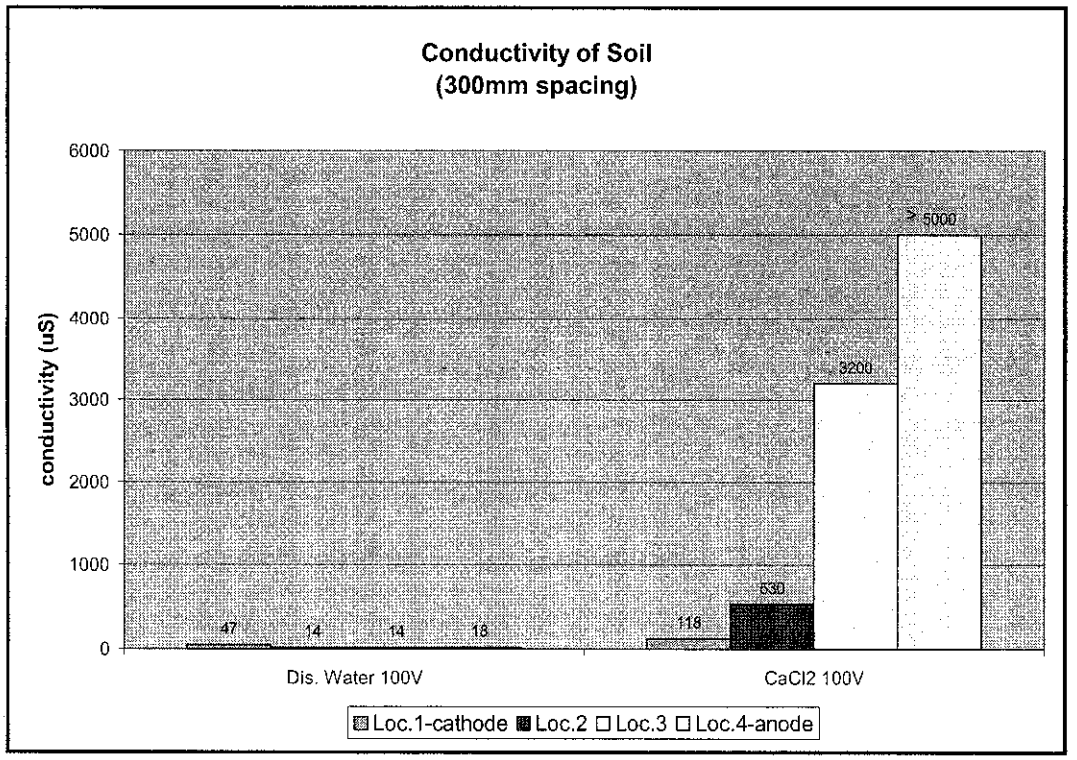


Figure 4.80 Conductivity variation in test samples 300 mm spacing

Figures 4.68 and 4.69 show the voltage variation for tests using 600 mm spacing. For the test using $CaCl_2$, the overall trend shows that the voltage gradient gradually decreased from initial time to 168 hr for point 0-290 mm indicating high conductivity till the end of test results. This was possibly due to calcium ions remaines ionic in the pore fluid because calcium ions could not precipitate in an acidic environment. Close to the cathode from distance 290-300 mm, the voltage drop increased for increasing period of treatment due to increase resistivity. This was again possibly a result of precipitation and cementation. Figure 4.69 revealed the same trend of results for electroosmotic test using distilled water with a small voltage drop in the vicinity of the cathode indicating low resistivity zone because of low precipitation and cementation/pozzolanic activities in this zone.

Figure 4.70 and 4.71 give results of variation of voltage for test using $CaCl_2$ and distilled water with 150 mm spacing. Just like the case of treatment for the 300 mm spacing, Figure 4.70 shows a decreasing value of resistivity for 144 hr and 168 hr at the cathode denoting ionization activities. Figure 4.71 also shows the same approximate behavior as found in the treatment for 300 mm spacing using distilled water by exhibiting the high voltage drop for period 168 hr at the anode. As oppose to treatment using $CaCl_2$, the variation in voltage drop for all periods of treatment were small at the cathode. In general, as far as voltage variation was concerned, the major distinctive difference for treatment with $CaCl_2$ and distilled water lies in the magnitude and variation of voltage at the vicinity of the cathode. Electrochemical treatment results in a bigger voltage drop and bigger variation in voltage drop for all the treatment period while test with distilled water displayed smaller voltage drop and smaller variation in voltage drop. A general conclusion also could be deduced from Figure 4.80 which shows that conductivity decreased along the specimen from anode to cathode for electrochemical treatment but produced small conductivity value for electroosmotic treatment with the cathode (47 μS) having higher conductivity magnitude than the anode (18 μS). Figure 4.79 further demonstrated that for all treatment with $CaCl_2$, the value of conductivity at anode was always bigger than at cathode while treatment with distilled water exhibited smaller conductivity and being bigger at cathode than anode. In the following sections, a further

brief analysis was conducted on the constitutive elements, compounds and mineralogy of the soil after treatment.

4.3.3.1 XRF Analysis

Table 4.18 Results of XRF tests on samples after treatment

		Al_2O_3 content	SiO_2 content	CaO content	CuO content	Fe_2O_3 content	Cl content
1mol $CaCl_2$-anode 1 (within 3 mm from anode)	kCps	0.5	2.0	3.4	6762.9	1446.9	138.2
	(%)	0.379	0.912	0.194	68.0	14.6	16.2
1mol $CaCl_2$-anode 2 (within 3-40 mm from anode)	kCps	63.4	156.0	8.8	318.6	64.7	9.7
	(%)	29.1	60.8	0.55	1.49	0.615	1.40
1mol $CaCl_2$-cathode 1 (within 0-10 mm from cathode)	kCps	36.6	103.9	122.4	11.5	48.8	0
	(%)	24.3	55.7	11.1	0.0749	0.888	0
1mol $CaCl_2$-cathode 2 (within 10-20 mm from cathode)	kCps	47.0	118.7	48.6	30.1	58.6	0
	(%)	27.9	59.4	4.02	0.184	0.845	0
1mol $CaCl_2$-cathode 3 (within 20-40 mm from cathode)	kCps	72.0	166.0	10.2	6.3	66.4	0
	(%)	30.7	61.7	0.596	0.0026	0.596	0
Distilled water-anode	kCps	69.7	162.6	2.9	14.5	65.2	0
	(%)	30.5	61.6	0.169	0.0026	0.588	0
Distilled water-cathode	kCps	76.7	177.4	2.7	6.4	66.9	0
	(%)	30.9	62.3	0.149	0.0009	0.558	0
Untreated soil	kCps	71.6	165.1	2.7	0	84.8	0
	(%)	30.7	61.7	0.158	0	0.772	0

Table 4.18 shows XRF results on various locations for tests using $CaCl_2$, distilled water and untreated soil condition. By observing the amount of formation of CaO (a component in CAH and CSH), and the reduction of Al_2O_3 and SiO_2 contents in test using $CaCl_2$, there was a clear indication that the major strength increase especially in the vicinity of the cathode was due to pozzolanic reaction resulting in a cementitious product (hydrated CAH and CSH). High temperature was observed at cathode due to pozzolanic reaction and high resistance of current flow. Close to the anode, hardening due to cementation effect was also observed since a higher value of CaO was indicated compared to the value in untreated soil and test using distilled water. Stabilization at cathode and anode was also due to precipitation of CuO. Some precipitation of hydroxides could also occur at cathode. Besides precipitation and cementation, strength gain in test using $CaCl_2$ was also contributed by consolidation/dewatering process, dessication by heat generation at the electrodes especially at cathode and some fabric changes due to cation replacement. Note that some amount of chlorine (Cl) was also detected within the vicinity of the anode which could have caused precipitation of salts. The strength gain in case of the electroosmotic treatment was contributed predominantly by consolidation/dewatering process and cation replacement shown by the changes in Atterberg limits especially changes in PI. Changes in Atterberg limits increase the salt concentration or salinity causing improvement of the soil structure in the form of better cementation bonding of soil particle and consequently increased the shear strength and reduced the sensitivity of clays (Lo and Ho, 1990). Another contributing factor to strength was also due to precipitation of CuO and hydroxides.

4.3.3.2 XRD Analysis

X-ray diffraction tests and analysis were performed to compare the mineralogical composition of some of the treated and untreated soil in the electrochemical box tests using 300 mm spacing. The comparisons are given in Figures 4.81, 4.82, and 4.83.

Figure 4.81 shows XRD patterns comparing between untreated soil (black color pattern) and 1mol $CaCl_2$-100V at anode (red color pattern). It could be seen that the collapse of the peak for the sample using 1mol $CaCl_2$-100V at 27.2° indicates mineral alteration in

the 1mol $CaCl_2$-100V sample. Figure 4.82 compares between untreated soil (black pattern) and treatment using distilled water (red pattern). Overall, not much change was observed but a change to a shorter peak at 27.2° occurred. Figure 4.83 shows comparison between untreated soil (black pattern) and 1mol $CaCl_2$-100V test sample taken within 10 cm from cathode (red pattern). The XRD pattern shows massive changes in peaks for the red pattern denoting high mineral alteration where in this case a big portion of the soil was possibly transformed to hydrated CAH and CSH gels.

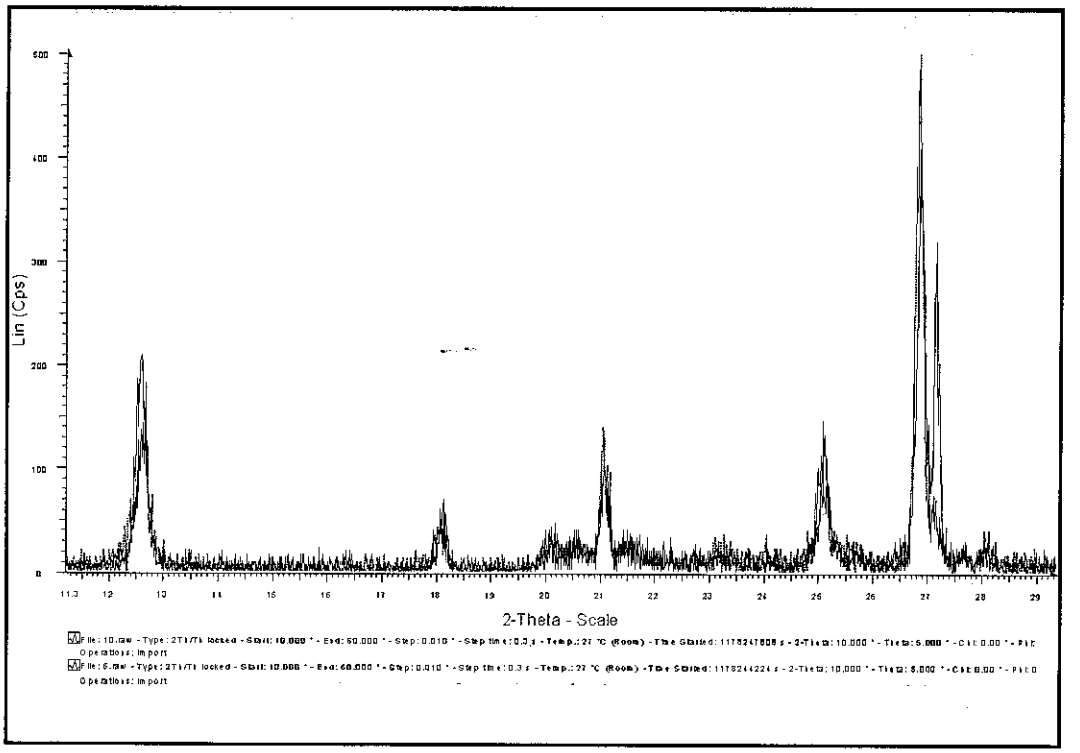


Figure 4.81 XRD comparison between untreated soil and test using 1mol $CaCl_2$ - 100V at anode

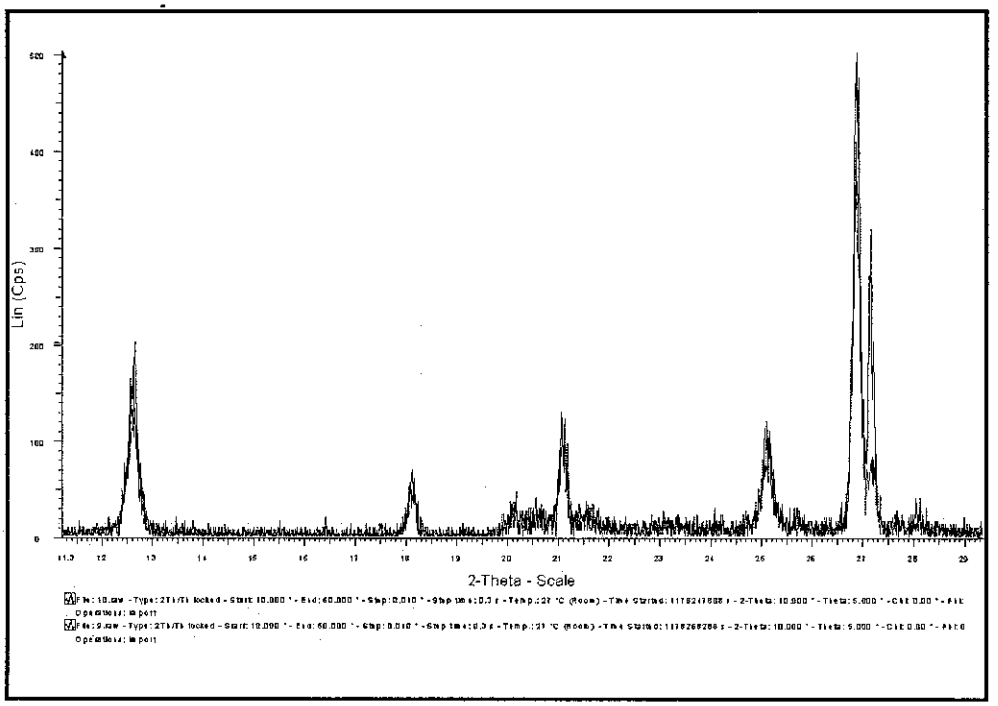


Figure 4.82 XRD comparison between untreated soil and test using distilled water at cathode

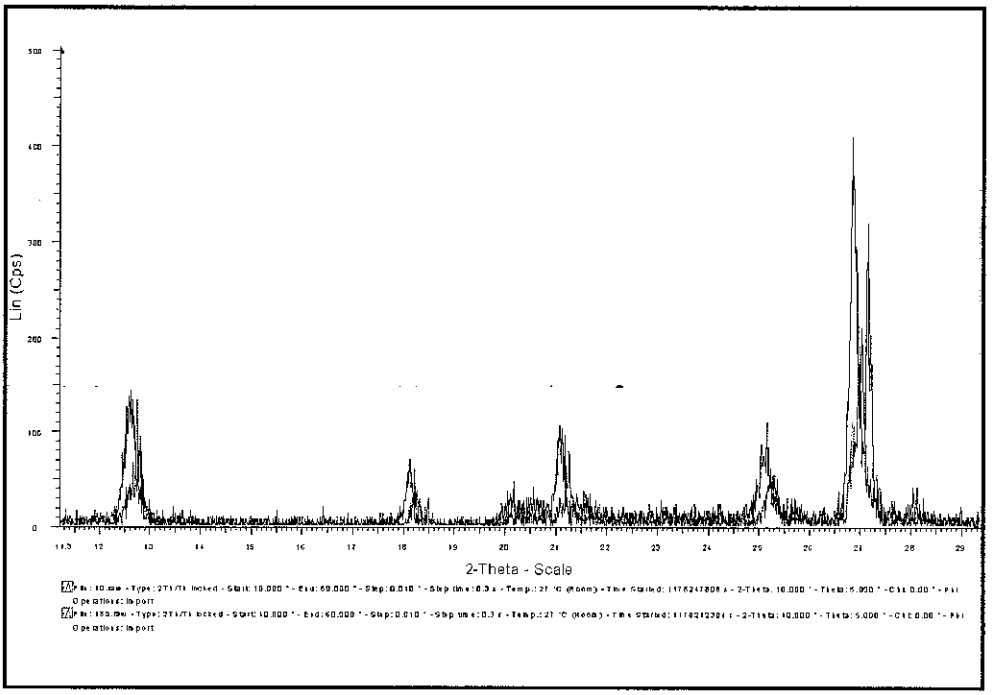


Figure 4.83 XRD comparison between untreated soil and test using 1mol $CaCl_2$-100V close to cathode

4.3.3.3 SEM and EDX Analysis

Some SEM results are shown below and the corresponding EDX results are given in Figures 4.88 and 4.89. A major difference in the arrangements and shapes of the individual particles with a much more flocculated condition could be seen in Figure 4.86 ($CaCl_2$, 0-10 mm from cathode) and Figure 4.87 ($CaCl_2$,10-20 mm from cathode) when compared with the untreated soil in Figure 4.84 or even with treatment using distilled water in Figure 4.85. Again traces of calcium which was a part of the hydrated CAH and CSH at cathode for treatment using $CaCl_2$ could be seen in the corresponding EDX results in Figure 4.89 as oppose to untreated soil in Figure 4.88. Hence both the SEM and EDX tests support the previous results obtained through the XRF test.

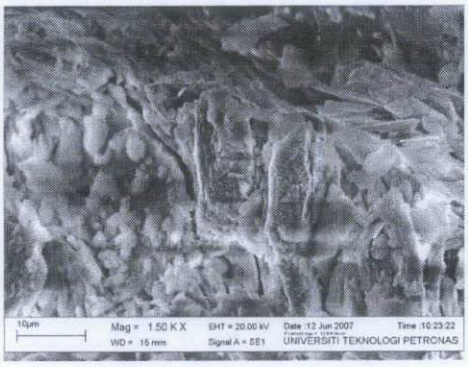


Figure 4.84 Untreated soil

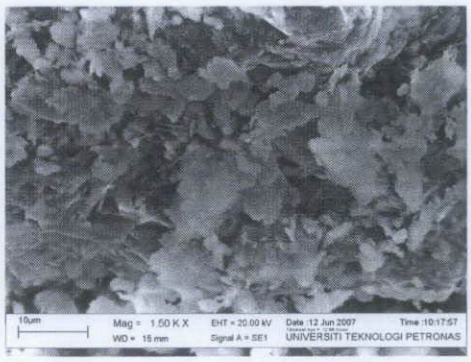


Figure 4.85 Soil treated with dist. water

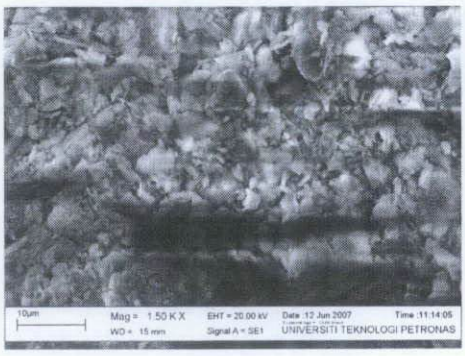


Figure 4.86 Soil treated with $CaCl_2$

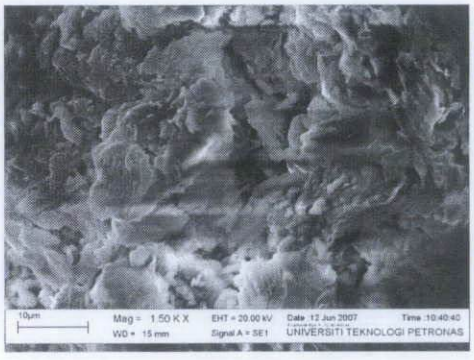


Figure 4.87 Soil treated with $CaCl_2$

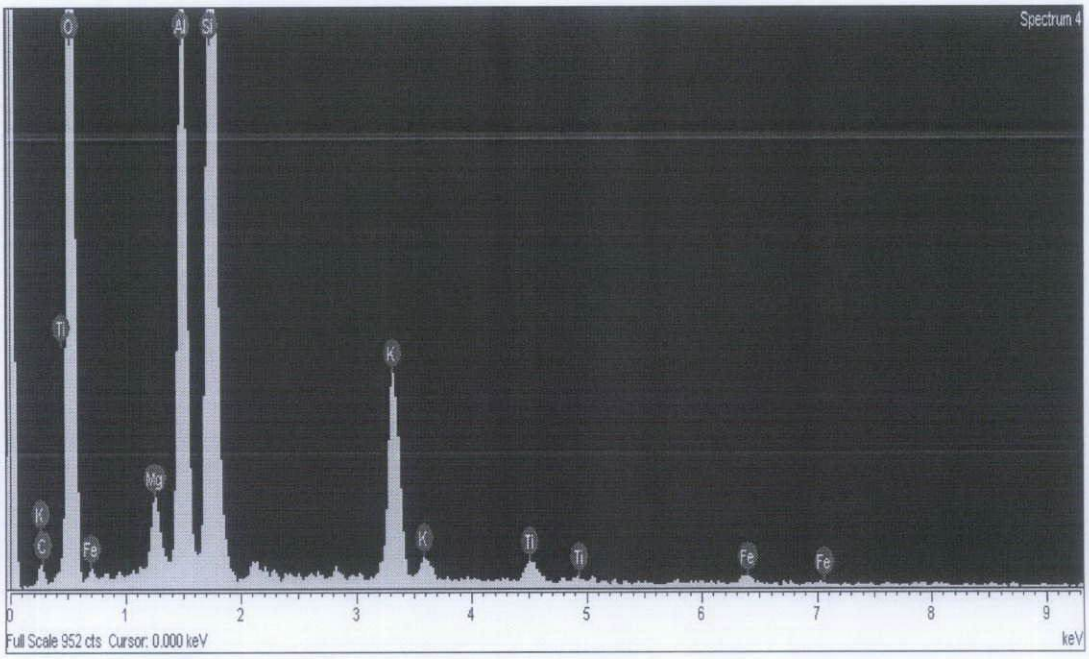


Figure 4.88 EDX results for untreated soil

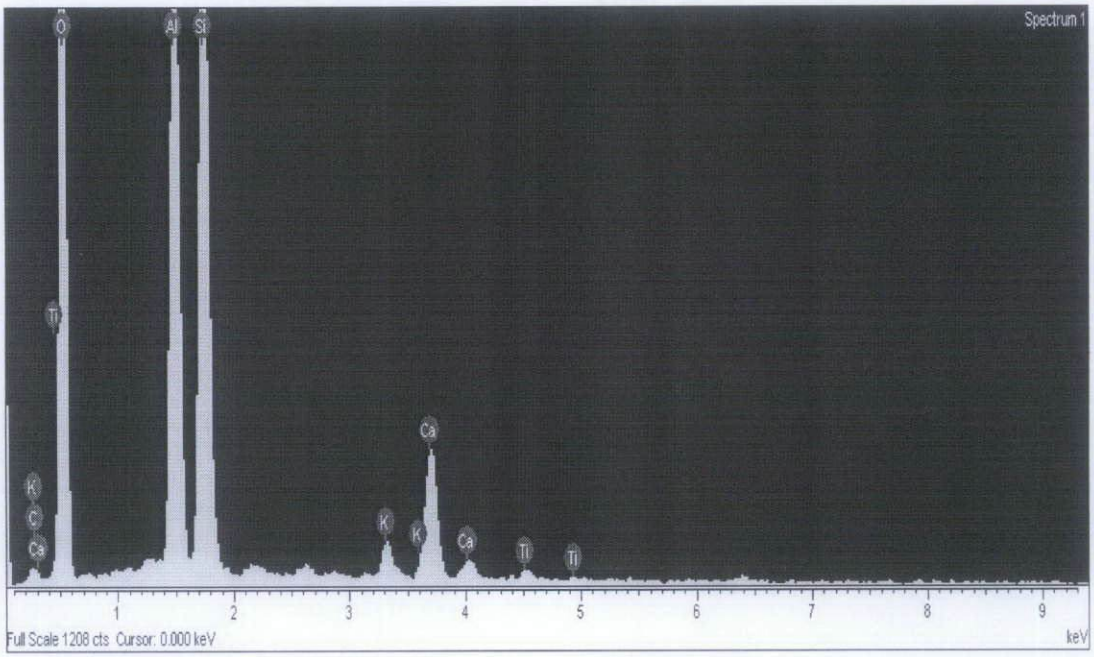


Figure 4.89 EDX results for test using 1mol-$CaCl_2$-100V

4.3.3.4 AAS Analysis

The AAS tests were conducted on the effluent from both the test using $CaCl_2$-100V and distilled water-100V for the 300 mm spacing. Table 4.19 gives the results of the AAS tests.

Table 4.19 Results of AAS tests for experiments using 300 mm spacing

Type of Test		CaCl 1mol				Distilled Water			
Voltage (V)		100				100			
Surcharge (kPa)		0				0			
Age of sample (hr)		3	20	30	48	3	20	30	48
Ph		10.31	10.13	11.1	-	7.44	8.66	8.54	9.0
Conductivity (uS)		460	80	350	-	70	74	-	100
Wt. of effluent (g)		110.68	125.21	57.36	25	106.4	186.4	18.8	91.1
Cation conc. (ppm)	Na^+	11.372	21.621	24.89	38.158	15.184	8.0171	4.834	10.036
	K^+	0	62.445	42.465	59.892	0	0	0	0
	Mg^{2+}	0.0084	0	0.0065	0.0060	0.0048	0.0081	0.0080	0.0073
	Ca^{2+}	459.49	0	174.0	173.70	0	0	0	0

Comparing both the results, the total effluent discharged from the cathode for tests with $CaCl_2$ and distilled water were 318.25 ml and 401.7 ml respectively showing the overall dewatering capability was less in the electrochemical treatment. The remaining reduction of water content was achieved through evaporation of water into the atmosphere and also consumed by the chemical reactions within the soil sample. Effluent at cathode shows a high pH value for test using $CaCl_2$ which accounted for the higher ability to dissolve silica and alumina in the soil sample and inducing precipitations of species. Higher conductivity value shows that despite the high alkaline environment, ionization activities were also higher than that in test using distilled water which accounted for the higher current value towards the end of the test. Looking at the cation concentration rows at the bottom part of Table 4.19, the effluent for both tests contained Na^+ ions showing that the

Na^+ ions on the clay surface were replaced by calcium ions in the case of the test using $CaCl_2$ and probably by H^+ in the distilled water case. Potassium ions (K^+) for test using $CaCl_2$ was high in the effluent showing that potassium ions was also probably replaced by Ca^{2+} cations on the clay surface. No K^+ was found in the effluent for test using distilled water indicating that the K^+ ions have not been replaced. Almost negligible amount of Mg^{2+} ions were displaced in both cases because magnesium ions were able to precipitate in alkaline condition. An interesting occurrence to be highlighted here was on the high contents of Ca^{2+} ions in the effluent from test using $CaCl_2$. Theoretically, just as in the case of Mg^{2+}, in an alkaline environment, Ca^{2+} should have precipitated and therefore no Ca^{2+} ions should have been discharged through the effluent. However, in the opinion of the author, although calcium ions were precipitated at the cathode and were also being consumed in the formation of CAH and CSH, but due to the excess of Ca^{2+} ions injected through the anode, some Ca^{2+} ions still remained ionic and were transported into the effluent.

4.3.4 Electrochemical tests in slopes – 200 mm spacing

A set of electrochemical tests using 1mol $CaCl_2$, 1mol $Ca(NO_3)_2$ and distilled water in slope condition, all with applied voltage of 100V were conducted to compare with results obtained in the previously conducted electrochemical box tests which were supposed to simulate flat ground condition. Table 4.19 shows the overall results obtained.

Table 4.20 Results of electrochemical tests in slopes -200 mm spacing

Type of Test	$CaCl_2$ 1 mol		$Ca(NO_3)_2$ 1 mol		Distilled Water	
Voltage (V)	100		100		100	
Surcharge (kPa)	0		0		0	
Moisture content	Anode	Cathode	Anode	Cathode	Anode	Cathode
	19.3	23.18	24.5	27.59	31.5	32.5
Strength (kPA)	93.2	116.5	70.0	87.4	5.83	7.45
Maximum current (mA)	808.4		427.3		8.2	

Referring to Figure 4.90, shear strength chart shows that test using $CaCl_2$ gave better strength than using calcium nitrate and very small strength was gained in the

electroosmotic treatment using distilled water. Higher strength was achieved at cathode than at anode in all the tests. Moisture content in Figure 4.91 again shows lower final moisure content in test using $CaCl_2$ than the rest. Again, the trend of higher strength gain and higher final moisture content at cathode in electrochemical treatment persisted in both electrochemical tests. The variation of current in Figure 4.92 indicated higher current value for test using $CaCl_2$ with a peak value of 808.4 mA comparing to 427.3 for tests using $Ca(NO_3)_2$ and 8.2 mA for distilled water. In conclusion, overall results demonstrated that the behavior for treatment of slope is almost similar to the treatment on flat ground condition in this small scale laboratory tests.

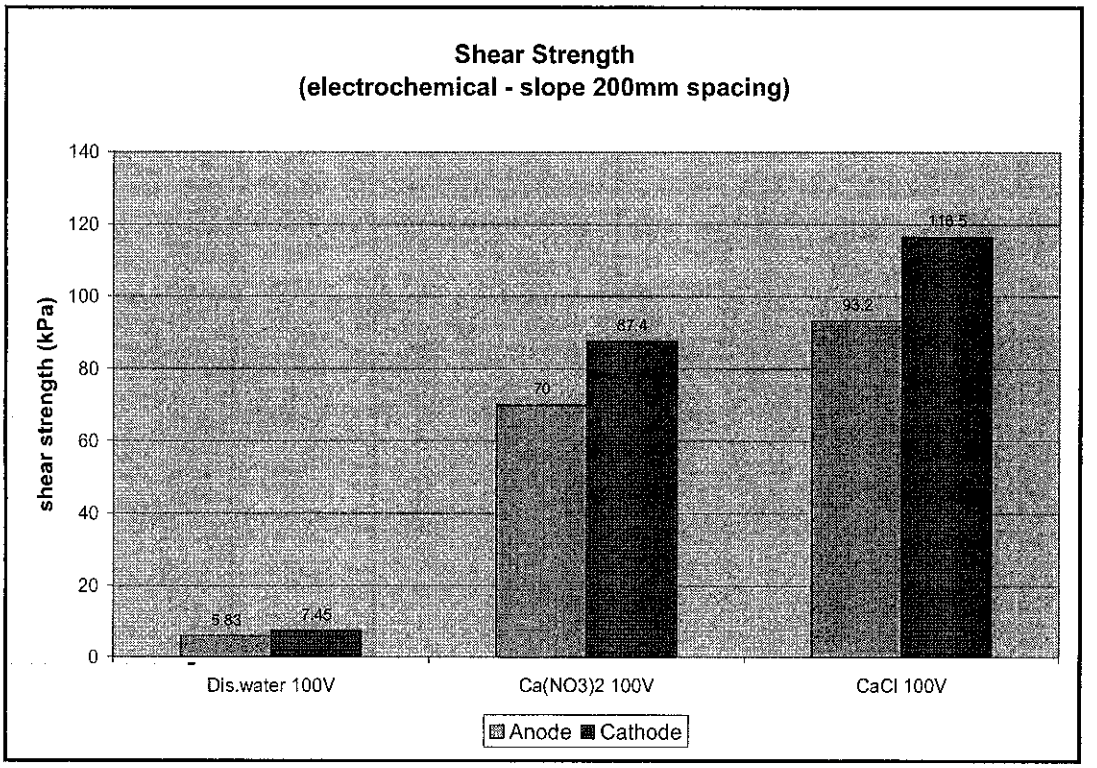


Figure 4.90 Shear strength for electrochemical test for slopes

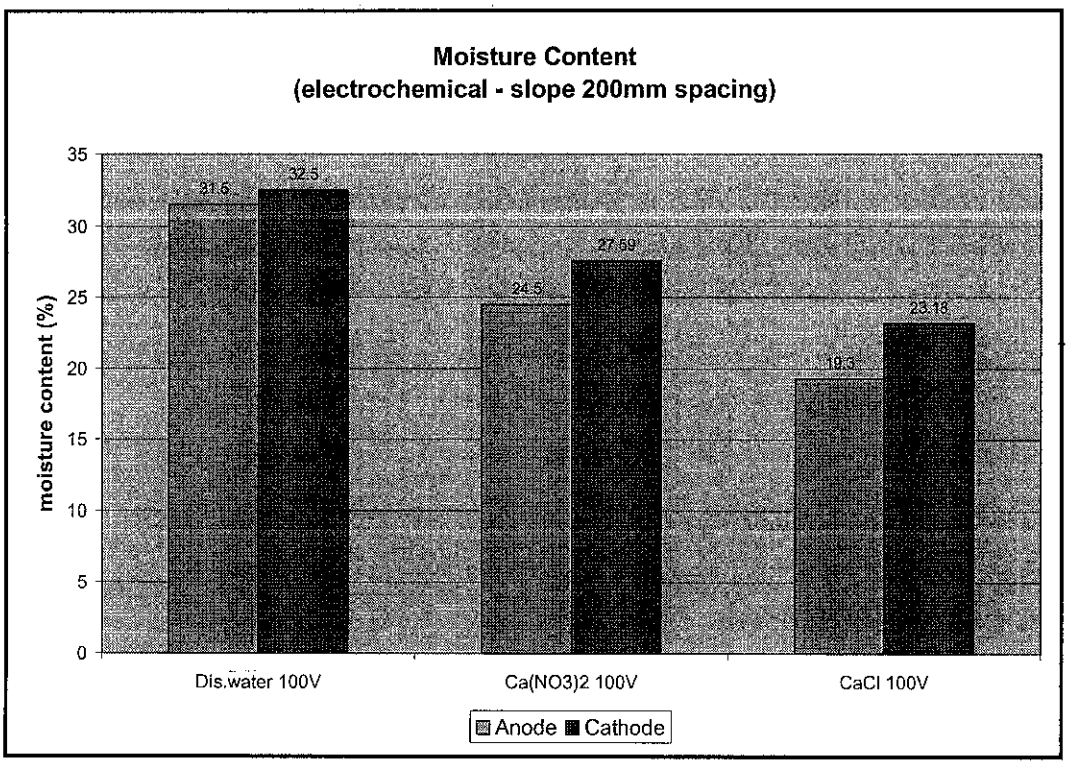


Figure 4.91 Moisture content for electrochemical test for slopes

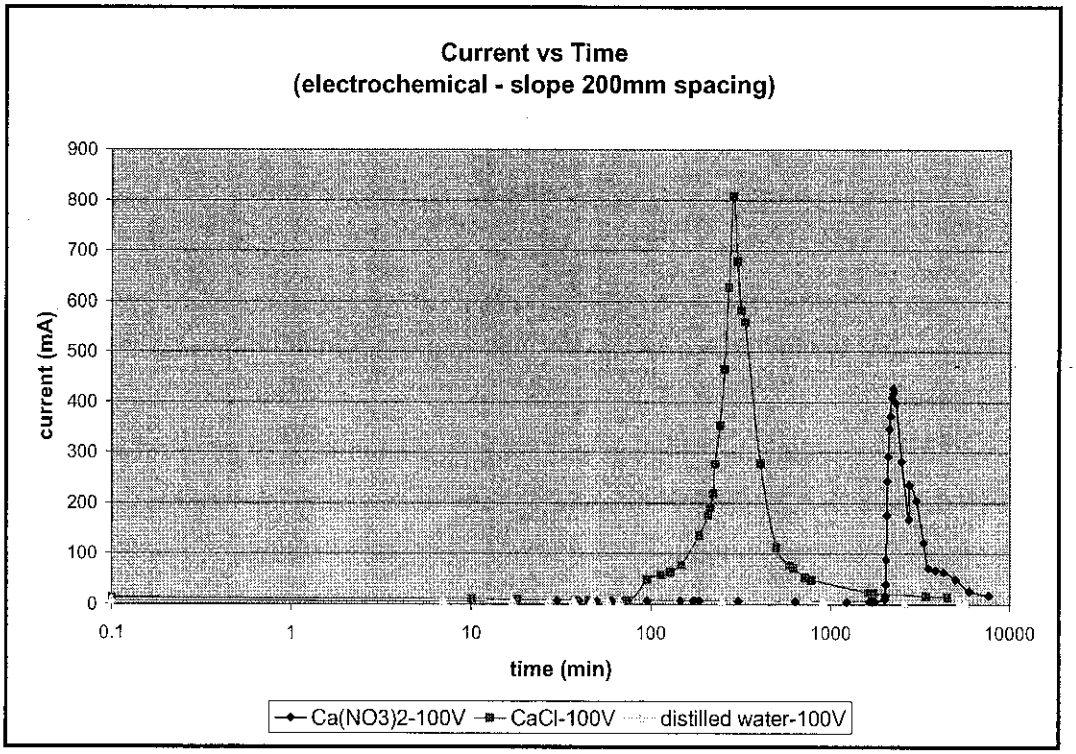


Figure 4.92 Variation of current vs. time for electrochemical test for slopes

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Altogether 53 electroosmotic and 30 electrochemical tests were conducted in this research. After conducting all the tests and applying the many varying parameters/variables, a better understanding of the behaviour and phenomenal effects of electroosmotic and electrochemical treatments on the selected kaolinite soil were achieved. Though this research was mainly carried out in the laboratory environment, at least in future, an approximate representation of the expected behaviour in field condition could very well be assumed in advance.

From the various results obtained in this research, it can be concluded that there were positive effects of both electroosmotic and electrochemical processes on the selected kaolinite soil. Several other conclusions may be drawn from this research;

i. Significant increase in shear strength especially in the electrochemical method along with the reduction in moisture content indicate that it is actually possible to stabilize kaolinite soil both in flat ground and slope conditions.

ii. The electroosmotic treatment using 200 volts with 5 kPa surcharge in the electroosmotic box tests produced an increase in shear strength of more than 1300% with a corresponding difference in final moisture content of only 20% when compared to the non-electroosmotic test using the same 5 kPa surcharge. The increase in shear strength when compared to the undisturbed sample taken at site (19.35 kPa) was more than 200%.

iii. The introduction of chemicals in the soil sample especially using $CaCl_2$ and $Ca(NO_3)_2$ in the electrochemical method produced better overall stabilization effect and overall enhancement in soil properties.

iv. The electrochemical treatment using 1mol $CaCl_2$-100 volts without any applied surcharge with 300 mm electrode spacing produced an increase of shear strength of more than 370% with the corresponding difference in final moisture content of about

35% when compared to the electroosmotic test using 100 volts with 10 kPa surcharge and 125 mm electrode spacing. The increase in shear strength when compared to the undisturbed sample taken at site was approximately 470%. These two comparisons indicate the tremendous enhancement was made possible through the introduction of appropriate chemicals.

v. A major improvement of soil in the electrochemical process was proven to be originating from the effect of ionic migration which took place in the system and not much from the electroosmotic dewatering process. This whole process among others causes dissolution of alumina and silica from clay minerals, and with the addition of calcium ions, the improvement was due to:
    - Formation of CAH and CSH which subsequently crystallized.
    - Formation of insoluble precipitates.

5.2 Recommendations for future studies

From both the methods carried out, the electrochemical method requires further elaborate experiments due to its complexities. In reality, the nature of electrochemical treatment in soil involves such a complex mechanism that several different chemical, electrical, and electrochemical processes become active within the soil-liquid medium simultaneously at any single time. The many governing factors that control the whole process cause difficulties in determining which parameters/variables is responsible for a particular effect or outcome during the course of treatment. The challenge is to isolate and clearly identify those parameters/variables so as to better understand the method enabling optimum treatment in future. For these, the following recommendations are proposed for future study;

i. Incorporating pore pressure transducers to detect changes in pore water pressure in both electroosmotic and electrochemical methods.

ii. Since pH and conductiviy changes are perhaps the two topmost governing factors dictating the effectiveness of electrochemical process, continuous logging of pH and conductivity throughout the test period should be taken into consideration.

iii. Instead of taking voltage at different interval, again, continuous reading in voltage along the sample is much more preferable.

iv. Other types of chemical such as aluminium sulfate or phosphoric acid could be added in the list of stabilizing chemicals.

v. Investigation in the effect of reverse polarity in the electroosmotic treatment of kaolinite soil should be included in future studies.

vi. Using aluminium or different electrodes with the appropriate chemicals in electrochemical treatment.

vii. Corrosion of the electrodes was a major problem in electrochemical process. Finding a suitable inert electrode or electrode with better resistance to corrosion and yet produces strong stabilization effect will be of great advantage.

viii. Using longer duration of treatment with longer spacings.

ix. Employing depolarization technique preventing the formation and migration of hydrogen ions which hinders the stabilizing process. A comparison could be made to asses the efficiency of electrochemical stabilization with and without the depolarization technique.

x. Calculations and quantitative values based on available formula could be incorporated to substantiate electroosmotic and electrochemical effectiveness when treating this kaolinite soil.

xi. Some experiments in field condition to asses the actual performance of both the methods and to investigate the reliability of laboratory findings.

Bibliography

1. Acar, Y.B. & Alshawabkeh A.N. (1993). Principles of electrokinetic remediation. Environmental Science and Technology, 27, No. 13, 2638-2647.
2. Acar, Y.B. & Alshawabkeh, A.N. (1997). Theoretical and experimental modelling of multi-species transport in soils under electric fields. Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.
3. Acar, Y.B. & Gale, R.J. (1992). Electrochemical stabilization of soils and other porous media. United States Patent 5616235.
4. Acar, Y.B. & Hamed, J. (1990). Electrokinetic processing in waste remediation/treatment. Transportation research board, 70th annual meeting, Washington, DC, 1-30.
5. Acar, Y.B. & Hamed, J., Alshawabkeh, A.N. & Gale, R.J. (1994). Removal of cadmium (ll) from saturated kaolinite by application of electrical current. Geotechnique Vol. 44, No. 2, 239-254.
6. Adamson, L.G., Chilingar, G.V., Beeson, C.M. & Armstrong, R.A. (1965). Electrokinetic dewatering, consolidation and stabilization of soils. Engineering Geology, Vol. 1, No. 4, 291-304.
7. Adamson, L.G., Rieke, H.H., Grey, R.R. & Chilingar, G.V. (1967). Electrochemical treatment of highly shrinking soils. Engineering Geology, Vol. 2, 197-203.
8. Adamson, L.G., Quigley, D.W., Ainsworth, H.R. & Chilingar, G.V. (1967). Electrochemical strengthening of clayey soils. Engineering Geolog, Vol. 1, Issue 6, 451-459.
9. Ahmad, H., Leszczynska, D. & Thenanayagam, S. (2001). Waste containment by soil stabilization using electrokinetic grouting method. Institute for International Cooperative Environmental Research, Florida State University, Tallahossee, Florida.
10. Alshawabkeh, A.N. & Acar, Y.B. (1996). Electrokinetic remediation I: Theoretical model. Journal of Geotechnical Engineering Division, ASCE, Vol. 122, No. 3, 186-196.

11. Alshawabkeh, A.N. & Sheahan, T.C. (2003). Soft soil stabilization by ionic injection under electric fields. Ground Improvements, Vol. 7, No. 4, 177-185.
12. Alshawabkeh, A.N., Sheahan, T.C. & Wu, X. (2004). Coupling of electrochemical and mechanical processes in soils under DC fields. Mechanics of Material, Vol. 36, 453 -465.
13. Asavadorndeja, P. & Glawe, U. (2005). Electrokinetic strengthening of soft soil clay using anode depolarization method. Bulletin of Engineering Geology & Environment, Vol. 64, 237-245.
14. Assarson, K., Broms, B., Granholm S. & Paus K. (1971). Deep stabilization of soft cohesive soils. Linden Alimark, Sweden, p 20.
15. Aydin, M., Yano, T. & Kilic, S. (2004). Dependance of zeta potential and soil hydraulic conductivity on adsorbed cation and aqueous phase properties. Soil Sci. Soc. Am., Vol. 68, 450-459.
16. Bally, R.J. & Antonescu, I. (1961). The application of electroosmosis to soil stabilization. Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering, Paris, 1-11.
17. Barker, J.E., Rogers, C.D.F., Boardman, D.I., & Peterson, J. (2004). Electrokinetic stabilization: an overview and case study. Ground Improvement, Vol. 8, No. 2, 47-58.
18. Bell, F.G. (1992). Engineering Treatment of Soils, Chapman & Hall.
19. Bell, F.G. (1995). Lime stabilization of clay minerals and soils. Engineering Geology, Vol. 42, 223-237.
20. Bell, F.G. (1988). Lime stabilization of clay soils: Part 1, Basic principles. Ground Engineering, 21(1), 10-15.
21. Bell, F.G. & Coulthard, J.M. (1990). Stabilization of glacial deposits of the Middlesbrough Area with cementitious material. Proc. 6th International Congress, International Association of Engineering Geology, Amsterdam (ed. D.G. Price), Balkema, Rotterdam, Vol. 3, 1797-807.
22. Bergado, D.T., Anderson, L.R., Miura, N. & Balasubramaniam, A.S. (1996). Soft Ground Improvement in Lowland and Other Environments, ASCE Press.

23. Bergado, D.T., Sasanakul, I. & Horpibulsuk, S. (2003). Electro-osmotic consolidaition of soft Bangkok Clay using copper and carbon electrodes with PVD. Geotechnical Testing Journal, Vol. 26, No. 3, 277-288.

24. Bjerrum, L., Moum, J. & Eide, O. (1967). Application of electroosmosis to a foundation problem in a Norwegian quick clay. Geotechnique, Vol. 17, 214-235.

25. BS 1377 (1990). Methodes of test for soils for civil engineering purposes. British Standards Institution, London.

26. Casagrande, L. (1951). Electroosmotic stabilization of soils. Journal of Boston Society of Civil Engineers, Vol. 39, 51-83.

27. Casagrande, L. (1952). Electrical stabilization in earthwork and foundation engineering. Proceedings of Conference on Soil Stabilization, Massachusetts Institute of Technology, Cambridge, 84-106.

28. Casagrande, L. (1983). Stabilization of Soils by means of electroosmosis, State-of-the-Art. Journal of the Boston Society of Civil Engineers, Vol.69, No.2, 225-302.

29. Chappel, B.A. & Burton, P.L. (1975). Electro-osmosis applied to unstable embankment. Journal of the Geotechnical Engineering Division, ASCE, Vol. 101, No. GT8, 733-740.

30. Chappel, B.A. & Huggins, G. (1998). Effect of backfill strength and stiffness on slope stability. AusIMM'98-The Mining Cycle, Mount Isa, Australia, 213-217.

31. Chi, B.P.C. & Yang, J.S. (1985). Chemical grouting in Taipei Basin. Proc. 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, Vol. 3, 1693-1696.

32. Colemen, N.T. & Graig, D. (1961). The spontaneous alteration of hydrogen clay. Soil Science, Vol. 91, 14-18.

33. Diamond, S. & Kinter, E.B. (1965). Mechanisms of soil lime stabilization. High Res. Rec., 92, 83-102.

34. Eades, J.L. & Grim, R.E. (1960). Reaction of hydrated lime with pure clay minerals in soil stabilization. High Res. Board, Bulletin 262, Washington, DC, 51-63.

35. Eggestad, A. & Foyn, T. (1984). Electro-osmotic improvement of a soft sensitive clay. Proceeding of the 8th European Conference on Soil Mechanics and Foundation Engineering, Helsinki, 567-603.

36. Esrig, M.I. (1968). Pore pressure, consolidation and electrokinetics. Journal of the soil Mechanics and Foundations Division, ASCE, Vol. 93, 109-128.

37. Esrig, M.I. (1971). Electrokinetics in soil mechanics and foundation engineering. Transactions of New York Academy of Sciences, Vol. 33, Series II, No. 2, 299-304.

38. Esrig, M.I. & Gemeinhardt, J.P. (1967). Electrokinetic stabilization of an illitic clay. Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 93, No. SM3, 109-128.

39. Eykholt, G.R. (1997). Development of pore pressures by non uniform electroosmosis in clays. Journal of Hazardous Material, Vol. 55, 171-186.

40. Eykholt, G.R. & Daniel, D.E. (1994). Impact of system chemistry on electroosmosis in contaminated soil. Journal of the Geotechnical Engineering Division, ASCE, Vol. 94, SM4, 899-922.

41. Fetzer, C.A. (1967). Electro-osmotic stabilization of West Branch Dam. Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 93, SM4, 85-106.

42. Fujihira, M., Shimizu, E., Konishi, T., Yasuda, S. & Shimizu, T. (2000). Fundamental study on soil prevention method of liquefaction using electrophoresis of fixative materials. Zairyo/Journal of the Society of Materials Science, 49, No. 1, 38-41.

43. Gray, D.H. (1970). Electrohardening of clay soils. Geotechnique, 20, No. 1. 81-93.

44. Gray, D.H. & Mitchell, J.K. (1967). Fundamental aspects of electroosmosis in soils, Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 93, SM6, 209-236.

45. Gray, D.H. & Somogyi, F. (1977). Electroosmotic dewatering with polarity reversal. Journal of Geotechnical Engineering, ASCE, Vol. 102, No. GT1, 51-54.

46. Gray, D.H. & Schlocker, J. (1969). Electrochemical alteration of clay soils. Clays and Clay Mineral, Vol. 17, 309-322.

47. Gurtu, J.N. (1977). Colloids, 6th edition, Pragati Prakashan, Meerut, India.

48. Hamir, R. (1997). Some aspects and applications of electrically conductive geosynthetic material. Doctoral Dissertation, University of Newcastle Upontyne.
49. Hamed, J., Acar, Y.B. & Gale, R.J. (1991). Pb (II) removal from kaolinite by electrokinetics, ASCE, Journal of Geotechnical Engineering Division, 117 (2), 241-271.
50. Harton, J.H., Hamid, S., Chedid, E.A. & Chilingar, G.V. (1967). Effects of electrochemical treatment on selected physical properties of a clayey silt. Engineering Geology, Vol. 2, Issue 3, 191-196.
51. Hilt, G.H. & Davidson, D.T. (1960). Lime fixation of clayey soils. High. Res. Board, Bulletin 262, Washington, DC, 20-32.
52. Ingles, O.G. & Metcalf, J.B. (1972). Soil Stabilization, Butterworths, Sydney.
53. Jayasekara, S. & Hall, S. (2007). Modification of the properties of salt affected soils using electrochemical treatments. Geotech Geol Eng, Vol. 25, 1-10.
54. Kassim, K.A., Taha, M.R. & Ahmad, K. (2003). Electrokinetic on a tropical residual soil. 2nd International Conference on Advances in Soft Soil Engineering and Technology, Putrajaya, Malaysia, 833-841.
55. Karol, R.H. (1968). Chemical grouting technology. Proceedings American Society Civil Engineers, Journal of Soil Mechanics and Foundations Division, Vol. 94, SM1, 175-204.
56. Lee, G., Abelkader, M.O. & Hamdani, S.K. (1982). Effect of the clay fraction on some mechanical properties of lime-soil mixtures. J. Institute High. Engr., Vol. 11, 3-9.
57. Little, D.N. (1987). Fundamentals of the stabilization of soil with lime. National Lime Association Bulletin, No. 332, 1-20.
58. Little, D.N. (1995). Stabilization of pavement subgrades and base courses with lime. Dubuque, Iowa, Kendall/Hunt Publishing Company.
59. Lo, K.Y. & Ho, K.S. (1990). Field test of Electroosmotic strengthening of soft sensitive clays. Canadian Geotechnical Journal, 28, 74-83.
60. Lo, K.Y. & Ho, K.S. (1991). The effect of electroosmotic field treatment on the properties of a soft sensitive clay. Canadian Geotechnical Journal. 28, 763-770.

61. Lockhart, N.C. (1983a). Electroosmotic Dewatering of Clays II. Influence of salt, acid, and flocculent. Colloids and Surfaces, 6(3), 239-251.

62. Lockhart, N.C. (1983b). Electroosmotic Dewatering of Clays III. Influence of clay type, exchangeable cations, and electrode material. Colloids and Surfaces, 6(3), 253-269.

63. Lorenz, P.B. (1969). Surface conductance and electrokinetic properties of kaolinite beds. Clays and Clay Minerals, Vol. 17, 223-231.

64. Loughnan, F.C. (1969). Chemical Weathering of Silicate Minerals. Elsevier, New York.

65. Mise, T. (1961). Electroosmotic dewatering of soil and distribution of the pore water pressure. Proceedings, 5th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, 255-258.

66. Mitchell, J.K. (1970). In-place treatment of soils. Journal of Soil Mechanics and Foundations Division, ASCE, Vol. 96, No. SM1, 73-101.

67. Mitchell, J.K. (1981). Soil improvement-State of the Art Report. Proceedings, 10th ICSMFE, Stockholm, Vol. 4, 509-565.

68. Mitchell, J.K. (1991). Conduction phenomena from theory to geotechnical practice. Geotechnique 41, No. 3, 299-340.

69. Mitchell, J.K. (1993). Fundamentals of soil behaviour. 2nd edition, John Wiley & Sons Inc., New York, USA.

70. Mitchell, J.K. & Hopper, D.R. (1961). Influence of time between mixing and compaction on properties of lime stabilized expansive clay. High Res. Board, Bull. 304, Washington, DC, 14-31.

71. Mitchell, J.K. & Wan T.Y. (1977). Electro-osmotic consolidation – Its effects on soft soil. Proceedings of 9th International Conference on Soil Mechanics and Foundation Engineering, Tokyo, 219-224.

72. Mohamed, A.M.O. (2000). Electrochemical treatment of polluted soils. Proceedings of the International Offshore and Polar Engineering Conference, Seattle, USA, Vol. 2, 477-484.

73. Mohamed, A.M.O. & Antia, H.E. (1998). Geoenvironmental Engineering. Elsevier, Amsterdam, 707.

74. Naggar, M.H. & Routledge, S.A. (2004). Effect of electro-osmotic treatment on piles. Ground Improvement, Vol. 8, No. 1, 17-31.

75. Nuground (2004). Introduction to Electrokinetics and the use of EKG.

76. Owen, G.W. & Knowles, P.R. (1994). Steel Designers Manual, 5th edition. Blackwell Science, Oxford.

77. Ozkan, S., Gale, R. J. & Seals, R. K. (1998). Chemical stabilization of kaolinite by electrochemical injection. Soil Improvement for Big Digs, Boston, Massachusettes, 1-17.

78. Page, M.M. & Page, C.L. (2002). Electromediation of contaminated soils. Journal of Enviromental Engineering, ASCE, Vol. 128, 208-219.

79. Pamukcu, S. (1997). Electro-chemical technologies for in-situ restoration of contaminated subsurface soil. EJGE paper 1997-04, 1-34.

80. Phadungchewit, Y. (1990). The role of pH and soil buffer capacity in heavy metal retention in clay soils. Ph.D. Thesis, McGill University, Montreal, Canada.

81. Potter, E.C. (1956). Electro-chemistry-Principles and applications. Cleaver Hume Press Ltd.

82. Probstein, R.F. & Hicks, R.F. (1993). Removal of contaminants from soils by electric field. Science, Vol. 260, 498-503.

83. Puppala, S.K.V. (1994). Evaluation of saturation effects and selected enhancement techniques in electrokinetic soil remediation, MSE Thesis, Lousiana State University, USA.

84. Rhodes, J.D., Manteghi, N.A., Shouse, P.J. & Alves, W.J. (1989). Soil electrical conductivity and soil salinity: New formulations and calibrations. Soil Sci. Soc. Am. J., Vol. 53, 433-439.

85. Shang, J.Q. (1997). Electrokinetic dewatering of clay slurries as engineered soil covers. Canadian Geotechnical Journal, Vol. 34, 78-86.

86. Shang, J.Q. & Dunlap, W.A. (1996). Improvement of soft clays by high voltage electrokinetics. Journal of Geotechnical Engineering Division, ASCE, Vol. 122, 274-280.

87. Shang, J.Q. & Ho, K.S. (1998). Electro-osmotic consolidation behavior of two Ontario clays. Geotectechnical Engineering Journal, Vol. 29, No. 2, 181-194.

88. Smoluchowski, N. V. (1921). Handbucher Electrizitat und des Magnetismus, Barth, J.A. ed. Leipzig, Germany, Vol. 2, 366-428.

89. Soderman, L.G. & Milligan, V. (1961). Capacity of frictional piles in varved clay increased by electroosmosis. Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering, Paris, Vol.2, 143-147.

90. Spiegler, K.S. (1958). Transport process in ionic membranes. Transaction of the Faraday Society, Vol. 54, 1408-1428.

91. Sprute, R.H. & Kelsh, D.J. (1975). Electrokinetic densification of hydraulic backfill-a field test. United States Bureau of Mine, Report of Investigation.

92. Sulaiman, Z.A. (1991). Investigation into the kaolin occurrences of Tapah-Bidor area, Perak. Geological Survey Department of Malaysia, Industrial Mineral Project (1986-1990), report No. 6, 1-18.

93. Sutton, (1987). Soil Improvement Committee-Admixture Report. 121-125.

94. Syed, S.B.A. (2000). Electroosmotic treatment on marine soil and slime. Master Thesis, University Sains Malaysia.

95. Thomas, T.J. & Lentz, R.W. (1990). Changes in soil plasticity and swell caused by electro-osmosis. American Society for Testing and Materials, Issue: N1095, 108-117.

96. van Olphen, H. (1963). An Introduction to Clay Colloid Chemistry, John Wiley, New York, 1963.

97. Vane, L.M. & Zang, G.M. (1997). Effect of aqueous phase properties on clay particle zeta potential and electroosmotic permeability: Implications for electrokinetic soil remediation process, Journal of Hazardous Materials, Vol. 55, Elsevier, Amsterdam, 1-21.

98. Wade, N.H. (1976). Slope stability by electroosmosis.Proceedings of the 29th Canadian Geotechnical Conference, Vancouver, Section X, 44-46.

99. Wan, T.Y. & Mitchell, J.K. (1976). Slope stability by electroosmosis. Proceedings, 29th Canadian Geotechnical Conference, Vancouver, Section X, 44-46.

100. West L.J., Steward, D.I., Binley, A.M. & Shaw, B. (1999). Resistivity imaging of soil during electrokinetic transport. Eng. Geology, Vol. 53, 205-215.

101. Wieczorek, S., Weigand, H. & Marb, C. (2004). Applying electrokinetic phenomena to the remediation of inorganic contaminants in the unsaturated zone: from lab to pilot scale experiments. Bavarian Environmental Agency, Josef-Vogl-Technology-Centre, Germany.

102. Yeung, A.T., Hsu, C.N. & Menon, R.M. (1997). Physicochemical soil contaminant interactions during electrokinetic extraction, Journal of Hazardous Materials, Vol. 55, Elsevier, Amsterdam, 221-238.

103. Zhinkin, G.N. (1960). Strengthening of structural bonds in clay soils as the result of electrochemical stabilization, Kolloidn. Zh., Vol. 1, 33-37.

APPENDIX A

Figure A1 Site in Bidor where soil samples were taken

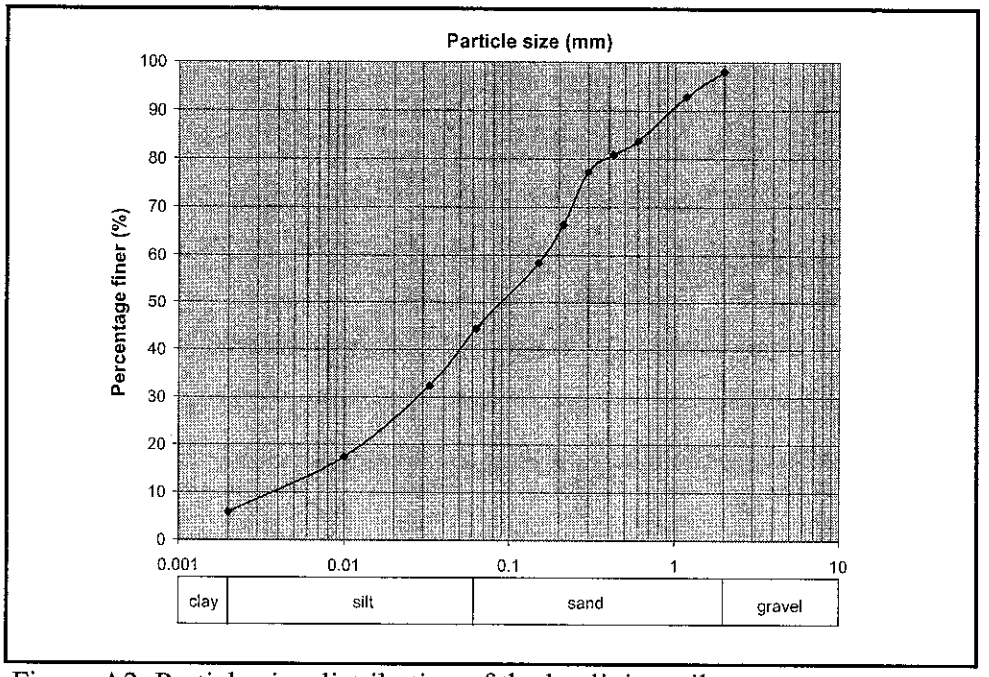


Figure A2 Particle size distribution of the kaolinite soil

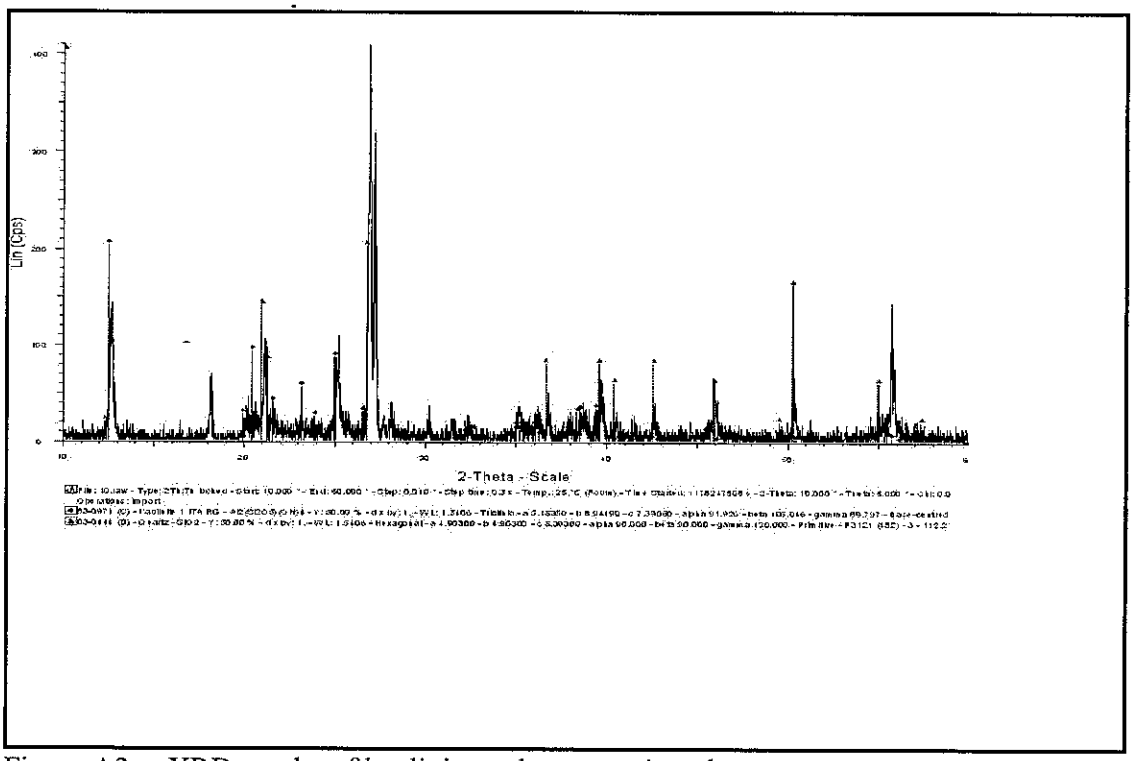


Figure A2a XRD results of kaolinite and quartz minerals

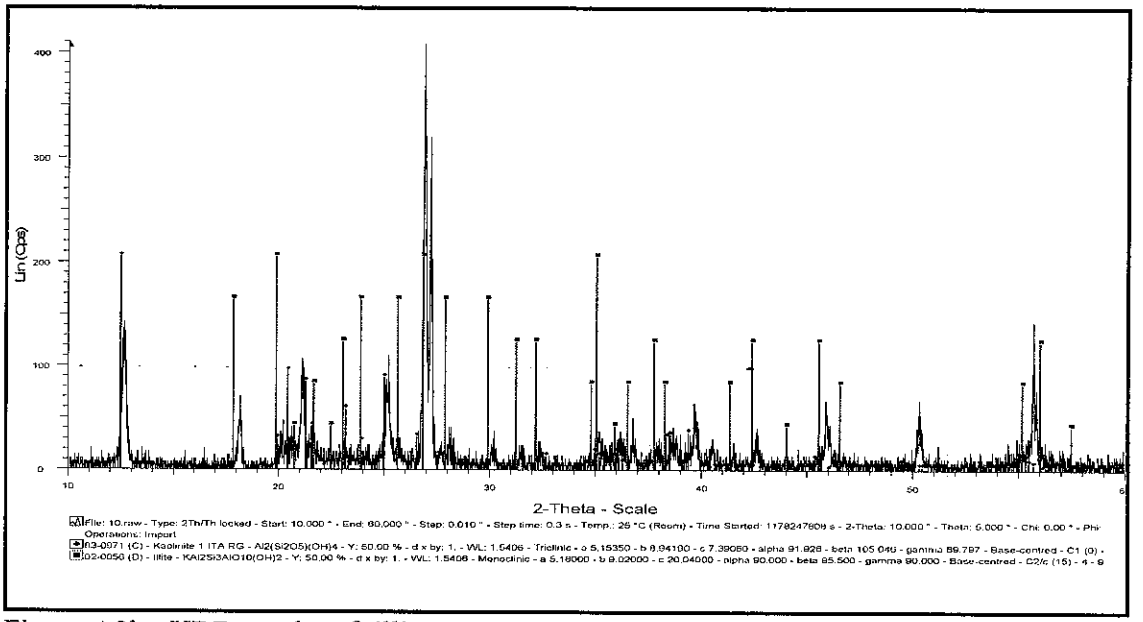


Figure A2b XRD results of illite

Table A1 Chemical composition of untreated soil

Chemical Composition	%	KCps
MgO	0.819	1.1
Al2O3	30.7	71.6
SiO2	61.7	165.1
P2O5	0.878	2.6
K2O	3.42	64.3
CaO	0.158	2.7
TiO2	1.21	24.9
Fe2O3	0.772	84.8
Rb2O	0.0213	21.9
Y2O3	0.0325	35.9
ZrO2	0.129	131.5
Nb2O5	0.00852	9.4
ThO2	0.0145	5.7
Compton	0.93	-
Rayleigh	1.53	-
Norm.	100.00	-

Table A2 Specifications of materials used as electrodes

Type of Electrodes	Specifications according to UNS standard	Thickness (mm)	Diameter (mm)
Copper disc	C110	0.7	95.0
Copper tube	- C110	1.0	28.0
Steel rod	SST-304L	-	10.0
Steel disc	SST-304L	1.6	95.0
Aluminium disc	1100	0.7	95.0
Brass disc	C360	0.7	95.0
Carbon disc	100%	4.0	95.0

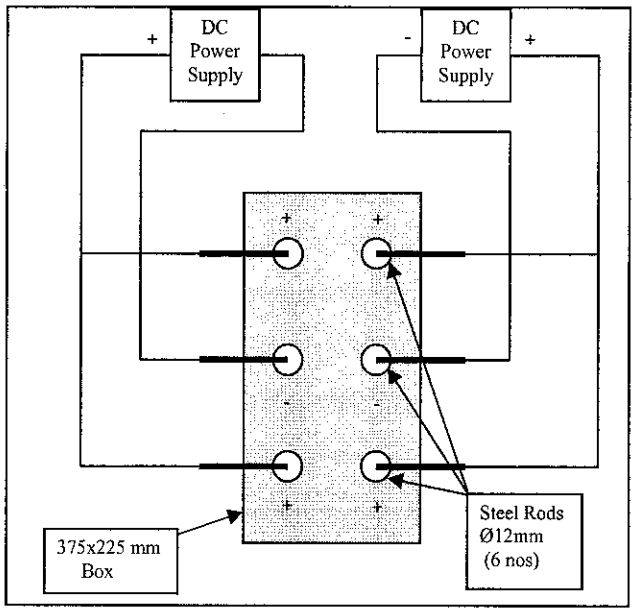


Figure A3 Connections of electrodes (type A) for electroosmotic treatment on slopes

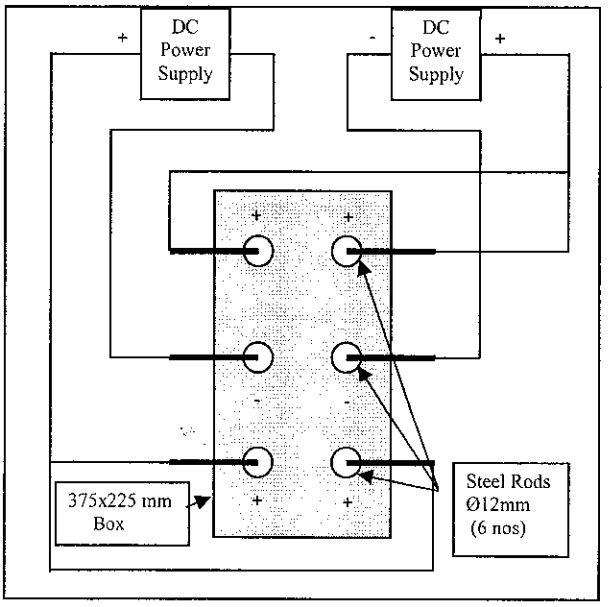


Figure A4 Connections of electrodes (type B) for electroosmotic treatment on slopes

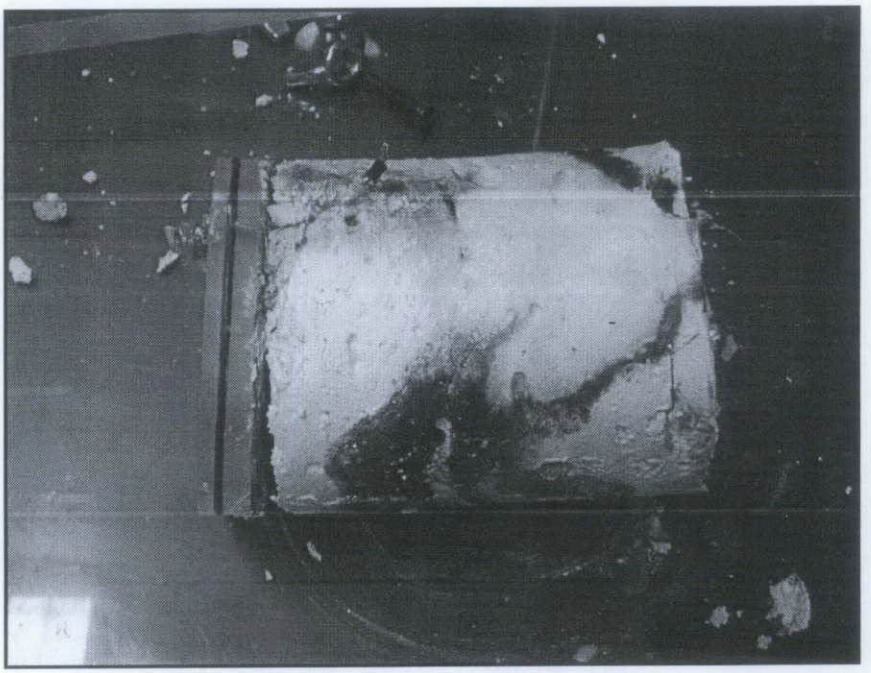


Figure A5 Soil sample after treatment in the electrochemical cell tests using 2mol $CaCl_2$-100V.

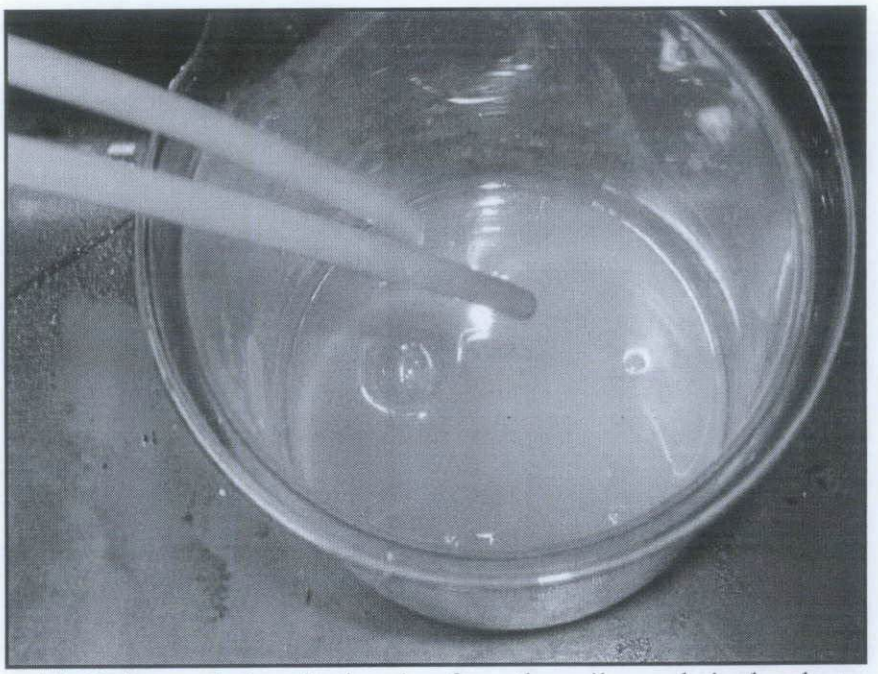


Figure A6 Yellow solution discharging from the soil sample in the electrochemical cell tests using $CaCl_2$-100V and $Ca(NO_3)_2$-100V

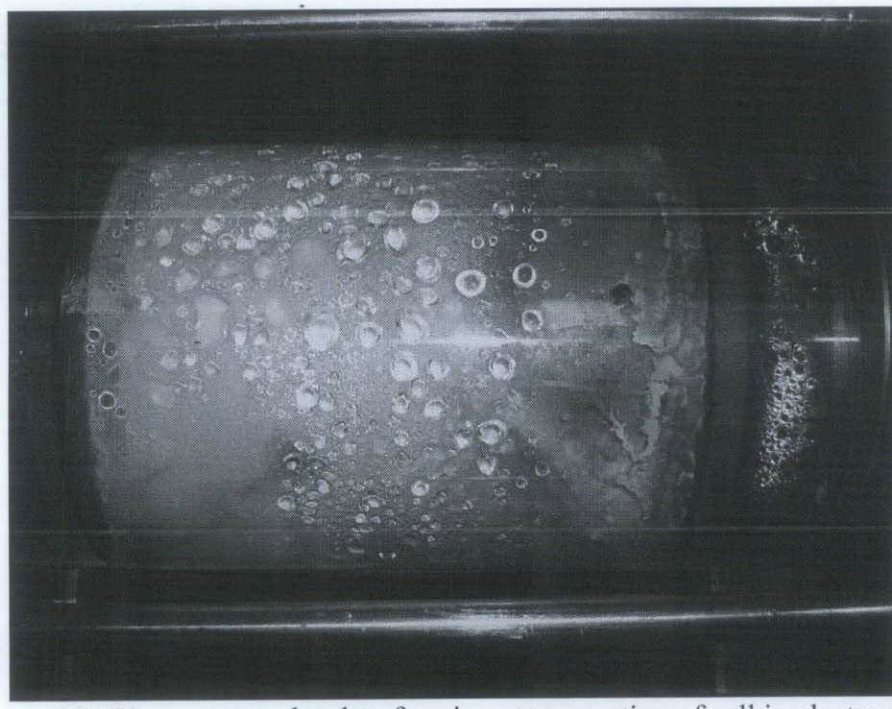


Figure A7 Water vapour droplets forming at top portion of cell in electrochemical cell tests using $CaCl_2$-100V and $Ca(NO_3)_2$-100V

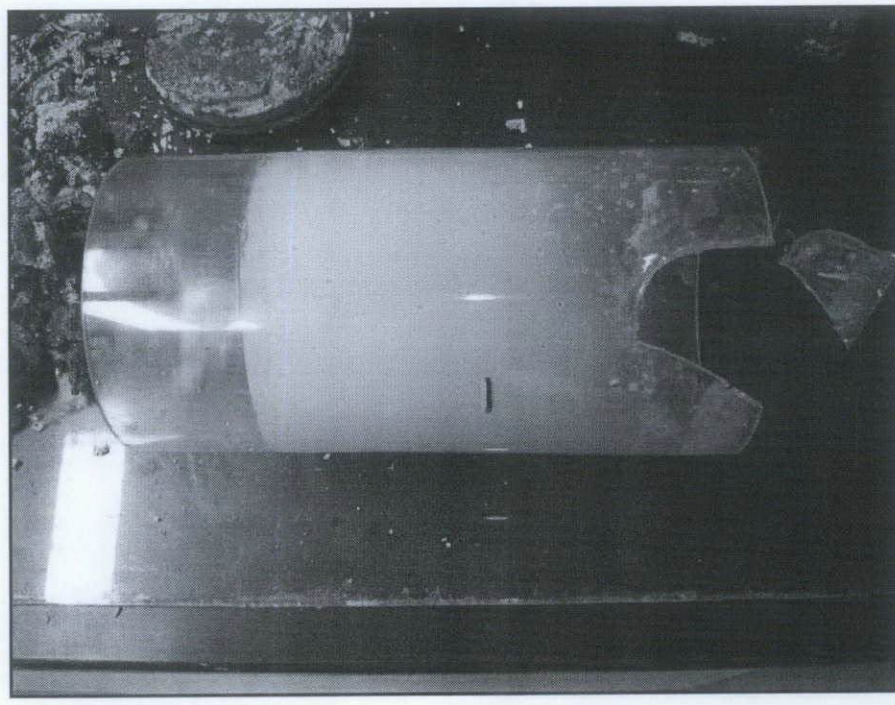


Figure A8 Perspex cylinder deformed due to high temperature during tests

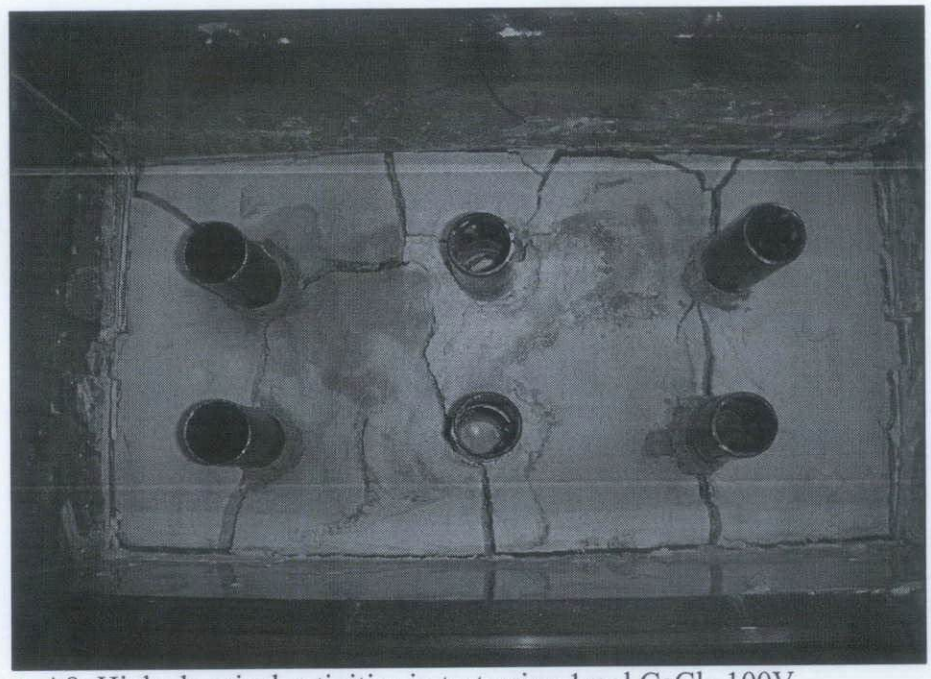


Figure A9 High chemical activities in test using 1mol $CaCl_2$-100V

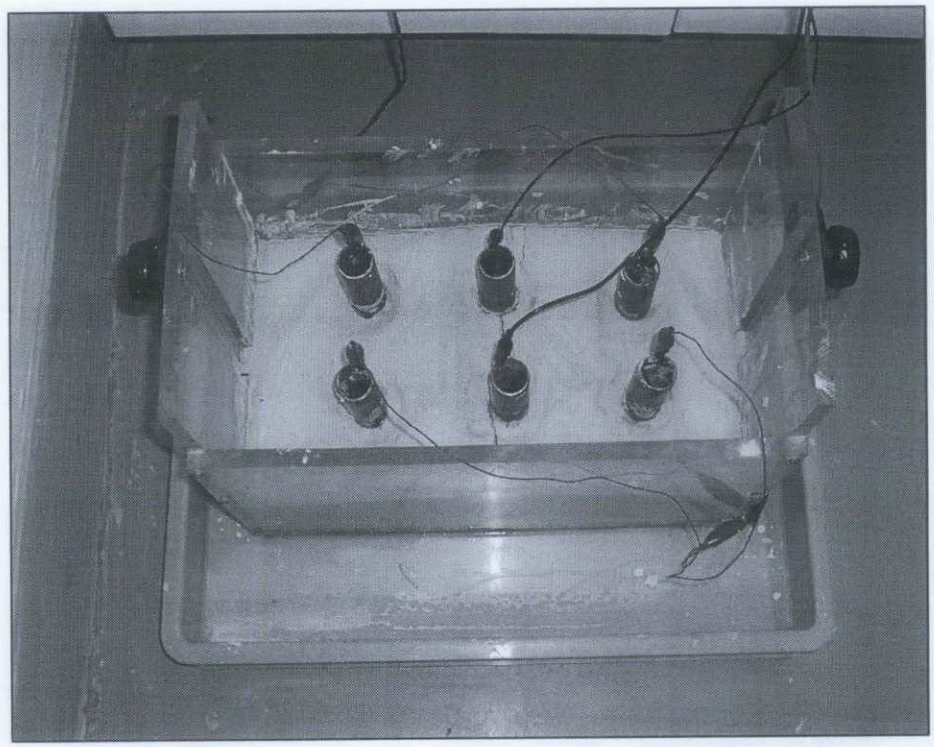


Figure A10 Low chemical activities in test using 1mol $Mg(OH)_2$-100V

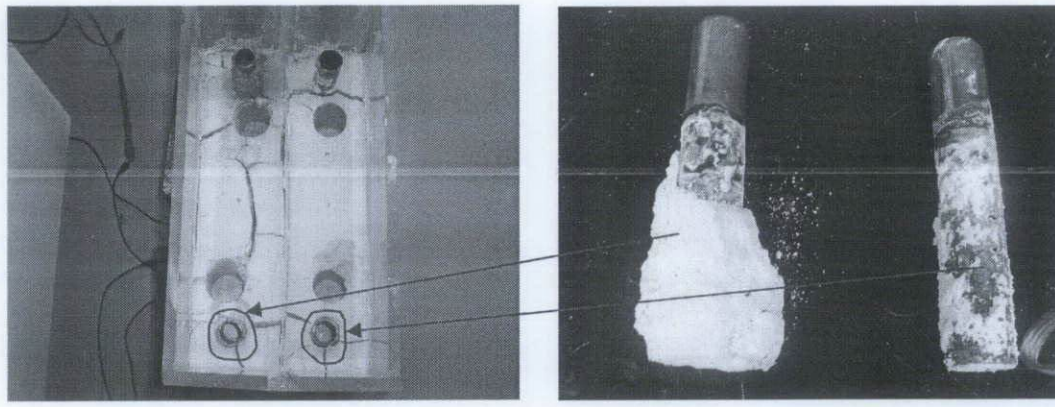


Figure A11 Cementitious material sticking to cathode (left) in test using $CaCl_2$ and cathode (right) with little cementitious material sticking in test using distilled water

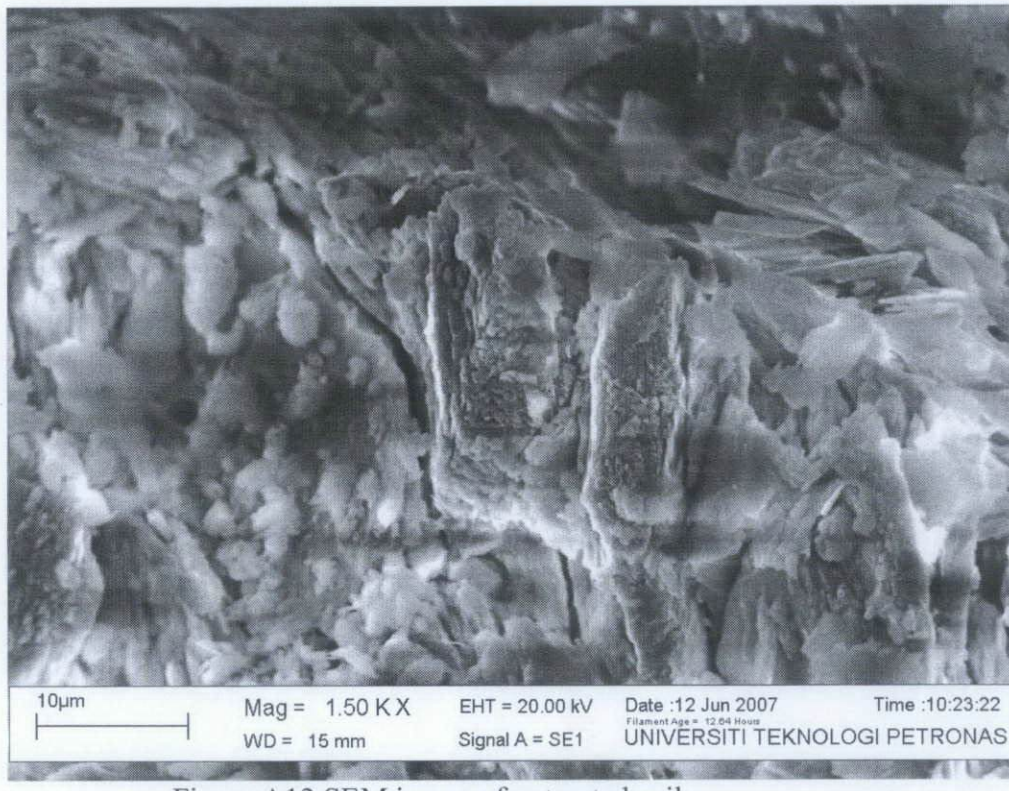


Figure A12 SEM image of untreated soil

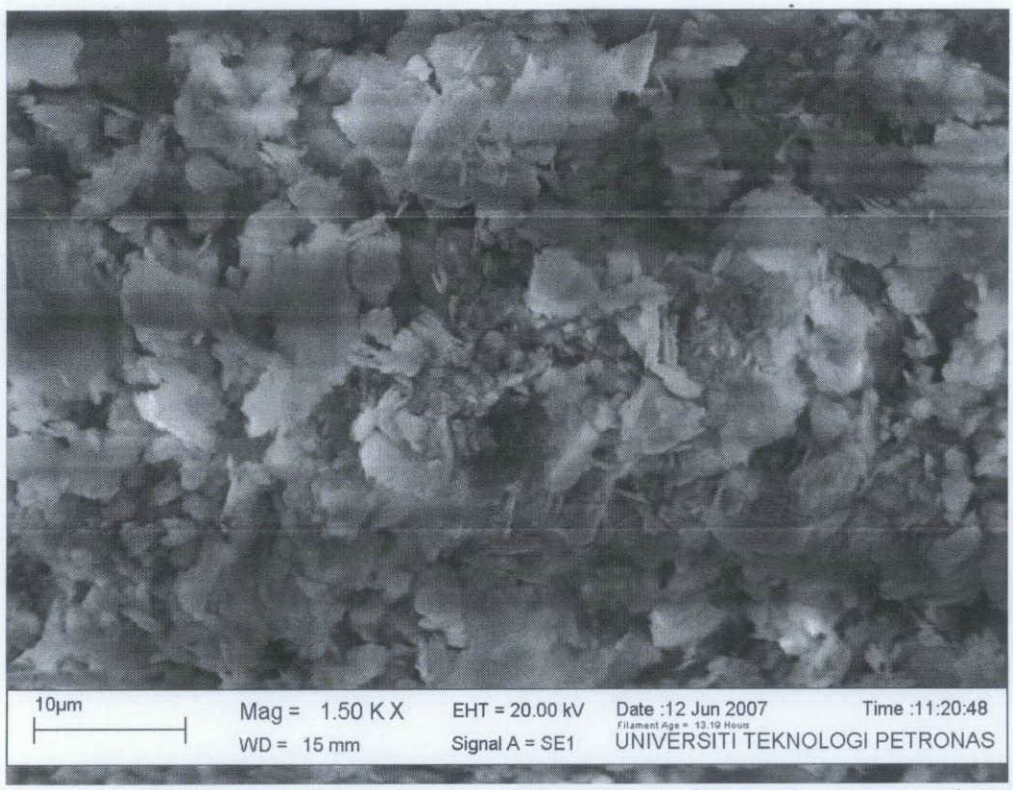


Figure A13 SEM image of treated soil in electrochemical box tests using 1mol $Ca(NO_3)_2$-100V

Figure A14 Corrosions and formation of oxides at anode in electrochemical cell tests

Figure A15 Very severe corrosion at anode in electrochemical cell tests

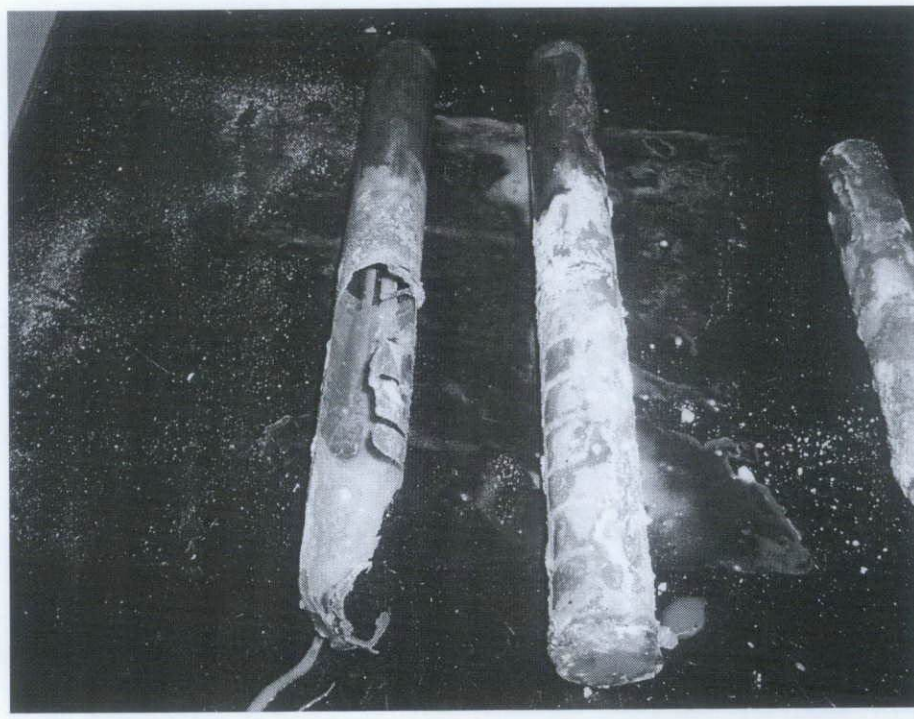


Figure A16 Severe corrosion at anode (left) in electrochemical box tests

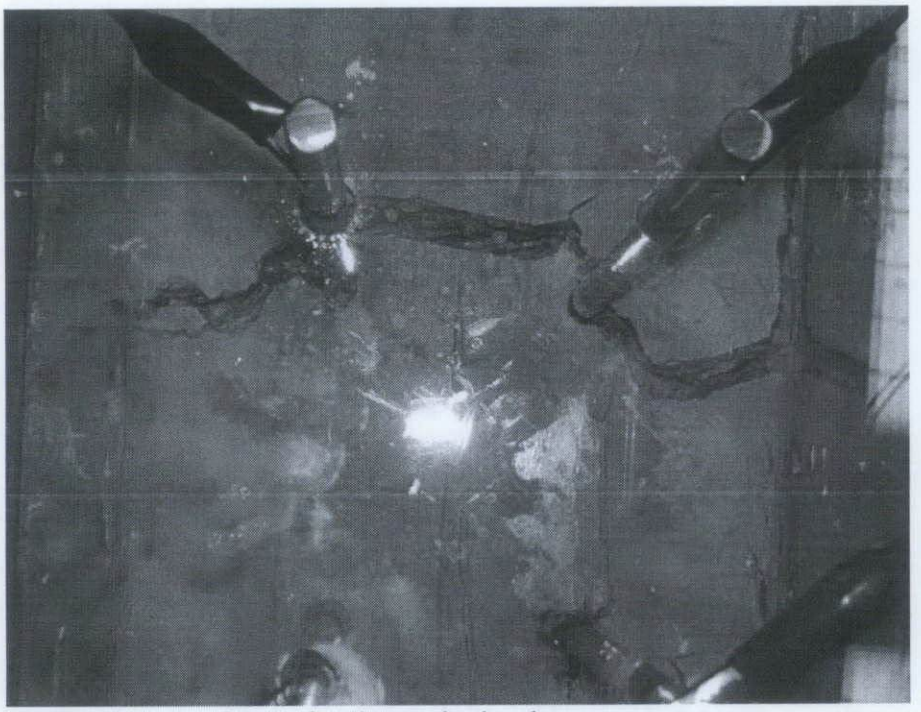


Figure A17 Cracking of soil at cathodes due to excess water